

High- p_T π^0 Production with Respect to the Reaction Plane in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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Measurements of the azimuthal anisotropy of high- p_T neutral pion (π^0) production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV by the PHENIX experiment are presented. The data included in this paper were collected during the 2004 RHIC running period and represent approximately an order of magnitude increase in the number of analyzed events relative to previously published results. Azimuthal angle distributions of π^0 s detected in the PHENIX electromagnetic calorimeters are measured relative to the reaction plane determined event-by-event using the forward and backward beam-beam counters. Amplitudes of the second Fourier component (v_2) of the angular distributions are presented as a function of π^0 transverse momentum (p_T) for different bins in collision centrality. Measured reaction plane dependent π^0 yields are used to determine the azimuthal dependence of the π^0 suppression as a function of p_T , $R_{AA}(\Delta\phi, p_T)$. A jet-quenching motivated geometric analysis is presented that attempts to simultaneously describe the centrality dependence and reaction plane angle dependence of the π^0 suppression in terms of the path lengths of hypothetical parent partons

in the medium. This set of results allows for a detailed examination of the influence of geometry in the collision region, and of the interplay between collective flow and jet-quenching effects along the azimuthal axis.

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I. INTRODUCTION

Over the past few years, experiments at the Relativistic Heavy Ion Collider (RHIC) have established that a dense partonic medium is formed in Au + Au collisions at $\sqrt{s_{NN}}=200$ GeV [1, 2, 3, 4]. This medium thermalizes very quickly [1, 5, 6, 7, 8, 9, 10, 11], is extremely opaque to the passage of high- p_T particles [12, 13], and the strong coupling of matter in the medium produces a system for which the ratio of shear viscosity to entropy (η/s) approaches zero [14, 15, 16, 17, 18]. Much of the current focus is on the extraction of key transport and thermodynamic characteristics of the matter produced in these collisions. Measurements of high- p_T parton propagation in the medium as well as medium-induced modification of the fragmentation parton spectrum and its products provide a critical tool for probing medium properties.

One of the most striking early results from RHIC was the observation of strongly suppressed production of high- p_T particles in central Au+Au events compared to appropriately scaled $p + p$ collisions [12, 13]. High- p_T partons are formed from hard scattering between the initial colliding partons, and these partons fragment into two or more jets of hadrons. When propagating through a dense volume of deconfined matter, these high- p_T partons are expected to scatter from color charges in the medium, losing energy through a combination of gluon bremsstrahlung radiation and collisional energy transfer to partons in the medium. These radiated gluons eventually fragment into hadrons at lower p_T , resulting in a depletion of the observed yields of hadrons at higher p_T .

A useful way to quantify the suppression of high- p_T hadrons is the nuclear modification factor (R_{AA}) where the $p + p$ cross section is scaled by the thickness function (T_{AA}) of the two Au nuclei

$$R_{AA}(p_T) = \frac{(1/N_{AA}^{evt})d^2N_{AA}^{\pi^0}/dp_T dy}{\langle T_{AA} \rangle \times d^2\sigma_{pp}^{\pi^0}/dp_T dy}.$$

PHENIX has measured a π^0 R_{AA} close to unity in both peripheral Au + Au collisions and Au collisions [19, 20], consistent with the expectation that these collisions would not produce an extended, dense medium. As the collisions become more central, R_{AA} decreases to about 0.2, indicating a stronger parton energy loss. Furthermore, the measured π^0 R_{AA} is nearly constant as a function of p_T , for $p_T \gtrsim 5$ GeV/c up to the highest currently accessibly p_T , 20 GeV/c [19].

These data can be well reproduced by models that calculate the energy lost by the hard scattered partons as they traverse the dense medium. The amount of energy-loss depends on the density of the medium [21], so measurements of high- p_T hadron suppression provide constraints on the transport coefficient $\langle \hat{q}^2 \rangle$, a measure of mean transverse momentum squared $\langle k_T^2 \rangle$ transferred by the medium to a high-energy parton. However, multiple models with different physical assumptions can reproduce the measured $R_{AA}(p_T)$ [22, 23]. The different models vary widely in how they include the crucial interference terms between multiple-scattering centers as well as the interplay between inelastic, elastic and flavor-changing processes during the parton's passage.

To discriminate between these models we need to increase our experimental control of the path length, since the amount of energy lost by a high- p_T parton strongly increases with the distance traveled through the medium. A quadratic dependence on the path length is predicted for a static medium if the dominant energy-loss mechanism is the bremsstrahlung radiation of gluons surviving the destructive interference caused by multiple scattering [22, 23]. For an expanding plasma the quadratic increase should be moderated to a linear dependence [24].

The centrality dependence of $R_{AA}(p_T)$ offers a probe of the path-length dependence of partonic energy loss. However, we can better test the path-length dependence by studying the azimuthal variation of the high- p_T suppression at a fixed centrality. Since the collision zone has a nearly elliptical shape in the transverse plane due to the non-central overlap of the colliding Au nuclei, partons that travel along the short axis of the nuclear overlap region lose less energy and should therefore be less suppressed. The key observable is then the two-dimensional modification factor $R_{AA}(\Delta\phi, p_T)$, where $\Delta\phi$ is the angle of emission with respect to the event plane. The azimuthal dependence of the spectra can be also parameterized by a Fourier expansion, where up to second order $\frac{dN}{d\Delta\phi} = N_0[1 + 2v_2 \cos(2\Delta\phi)]$, with v_2 being called elliptic flow coefficient. While both quantities characterize azimuthal asymmetries, historically and conceptually they have different roots. The notion of elliptic flow is primarily tied to lower p_T phenomena ("soft physics"), the domain where particle production is proportional to the number of participating nucleons (N_{part}), and positive v_2 arises from the *boost* to the mean p_T in the direction where the pressure gradient is highest (along the reaction plane). Conversely, $R_{AA}(p_T)$ and $R_{AA}(\Delta\phi, p_T)$ are commonly used to describe high p_T behavior (hard scattering, which scales with the number of binary collisions N_{coll}). When R_{AA} deviates from unity at high p_T , it becomes a valuable probe of the *loss* of energy/momentum

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in a particular direction. However, there is no clear separation between soft and hard regions, and both R_{AA} and v_2 are well-defined in the entire momentum range, so in this sense v_2 is sensitive to differential energy loss at high p_T .

PHENIX has measured high- p_T v_2 for π^0 particles from Au+Au collisions [25]. The energy-loss models that reproduce $R_{AA}(p_T)$ diverge in their predictions of the azimuthal anisotropy at high p_T . They generally underpredict the observed azimuthal variation of $R_{AA}(\Delta\phi)$, or equivalently, are unable to describe the p_T dependence of v_2 over the full range of p_T where one would naively expect them to be applicable [26, 27, 28]. These models include the hydrodynamical evolution of the medium, and therefore the high- p_T probe loses energy in a medium that is becoming spatially isotropic with time. Several early papers noticed that the measured v_2 values were larger than what one would expect from a completely opaque almond-shape collision zone [29, 30]. Other early energy-loss calculations came close to reproducing the measured $R_{AA}(\Delta\phi)$ [31, 32], but in these the plasma expansion was not taken into account, which resulted in unrealistically strong azimuthal anisotropy. Another calculation [33] has reproduced $R_{AA}(\Delta\phi)$, but in this model the Au nuclei were parameterized as hard-spheres instead of using a more realistic Woods-Saxon density profile, and this mechanism artificially increases the azimuthal dependence of the energy density.

One potential resolution of the problem with energy loss calculations not reproducing the measured azimuthal dependence of yields is a recent calculation that allowed the high- p_T parton to resonantly scatter with the medium [34] (and references therein), increasing the energy lost by a parton at plasma densities that correspond to temperatures near the critical temperature. This produces a sharper dependence of the energy-loss on the spatial variation of the medium's energy density and hence the model is able to simultaneously reproduce both $R_{AA}(p_T)$ and $R_{AA}(\Delta\phi)$. A critical check will be to examine whether the same parameters work for the full range of collision centralities.

In order to discriminate among all the models that attempt to reproduce $R_{AA}(\Delta\phi, p_T)$, the experimental challenge is to extend the range and increase the precision of observations which can be used to test different energy-loss models. In this paper we extend the range of published data on $R_{AA}(\Delta\phi)$ [25] by a) reaching higher p_T , and thereby moving to a p_T region that is completely dominated by the fragmentation of hard partons and reducing the possible contribution of particles from recombination [35], b) using finer bins in centrality, thus achieving less averaging of the path length, and c) reducing the statistical and systematic uncertainties to further constrain models. We present in this article measurements using data collected during the 2004 RHIC running period. These data represent a high-statistics sample of Au + Au collisions (approximately 50 times that of the 2002 RHIC running period) and therefore extend

our ability to measure $R_{AA}(\Delta\phi)$ and v_2 to much higher p_T with better precision.

II. EXPERIMENTAL DETAILS

The data presented in this paper were taken by the PHENIX experiment [36] in 2004 (RHIC Run-4), and represent the analysis of 821M minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The detectors involved in this analysis are the beam-beam counters [37] (BBC; triggering, centrality and reaction plane determination), the zero-degree calorimeter [38] (ZDC, centrality determination) and the electromagnetic calorimeter [39] (EM-Cal, π^0 measurement).

The BBCs are two groups of 64 hexagonal quartz Čerenkov radiator counters with photomultiplier readout surrounding the beampipe 144 cm up- and downstream (“North” and “South”) from the center of the nominal collision diamond, covering the $3 < |\eta| < 3.9$ pseudorapidity range and the full azimuth. Coincidence of signals in at least two photomultiplier tubes in both BBCs served as a minimum bias trigger and according to simulations it captured 92% of all inelastic collisions. The size of the total signal in the BBCs increases monotonically with collision centrality at this $\sqrt{s_{NN}}$. The collision vertex z was calculated from the difference between the fastest timing signals in the North and South BBCs, respectively, with $\sigma < 2.0$ cm resolution. Only events with $|z| < 30$ cm were analyzed.

The ZDCs are small tungsten/scintillator hadron calorimeters with quartz fiber lightguides and photomultiplier readout, located between the beampipes at 18 m North and South from the collision point. They measure non-interacting “spectator” neutrons in a cone of about 2 mrad, and their signal is double-valued as a function of centrality (it is low in very central and very peripheral collisions but large at mid-centrality). The correlation of ZDC *vs* BBC signals resolves this ambiguity and allows a precise measurement of the true centrality for all but the most peripheral collisions.

The reaction plane (spanned by the beam direction and the impact vector of the colliding nuclei) is determined event-by-event from the azimuthal charge distribution in the BBCs, after taking into account small nonuniformities (in the response of individual radiators, PMTs, electronics, etc.), using the assumption that over a large number of events the ϕ distribution of per-event reaction planes should be uniform. Due to the large rapidity gap between the central arm ($|\eta| < 0.35$) where π^0 s are measured, and the BBCs where the reaction plane is established, we assume that the reaction plane is unbiased and free from auto-correlations. However, the relatively coarse granularity of BBCs affects the resolution. Note that in this analysis precise knowledge of the reaction plane resolution, which depends strongly on centrality, is crucial. This will be discussed in detail in the next Section.

Neutral pions are measured by reconstructing their decay photons ($\pi^0 \rightarrow \gamma\gamma$) in the EMCal. The EMCal consists of 8 sectors at midrapidity ($|\eta| < 0.35$), covering a total of $2 \times 90^\circ$ in azimuth. Six sectors are lead/scintillator (PbSc) sampling calorimeter with photomultiplier readout and $5.5 \times 5.5 \text{ cm}^2$ granularity, two sectors are lead/glass (PbGl) Čerenkov counters with $4 \times 4 \text{ cm}^2$ granularity and photomultiplier readout. The two detectors are $18X_0$ and $16X_0$ radiation lengths deep, respectively, both ensuring essentially full containment of electromagnetic showers in the relevant energy range. The *in situ* energy resolution is well reproduced by simulation both in PbSc and PbGl: the π^0 peak positions and the widths both agree with the data to better than 1 MeV over the entire momentum range. Therefore, the error on the energy (and momentum) scale is less than 1%. Timing resolution σ_t is ~ 450 ps and ~ 650 ps for the PbSc and PbGl, respectively, allowing the rejection of neutrons and antineutrons up to a few GeV/c transverse momentum, which would otherwise be a major source of neutral showers up to a few GeV energy. At sufficiently high transverse momenta, decay photons from a nearly symmetric ($E_{\gamma_1} \approx E_{\gamma_2}$) decay may produce showers in the calorimeter that start to merge into one reconstructed cluster. In the PbSc this effect is first visible around $p_T \sim 10$ GeV/c, at the upper end of the p_T region considered in this paper. Due to its higher granularity and smaller Molière-radius the PbGl is immune to this “merging” problem up to $p_T \sim 15$ GeV/c. The hadronic response, timing properties and other sources of systematic errors are very different for the two calorimeter types. Therefore, when extracting the ϕ -integrated R_{AA} , which serves as absolute normalization, the PbSc and PbGl were analyzed separately and the results combined to decrease the total systematic uncertainty.

III. DATA ANALYSIS

A. Centrality

As mentioned, the minimum-bias trigger in the Run-4 PHENIX configuration is supplied by the BBCs, and the correlation of the charge deposited in the BBCs with energy deposited in the ZDCs provided a determination of the centrality of the collision. The elliptic flow measurement presented in this paper is measured in seven bins of the centrality range 0-92%, with lowest corresponding to the most central: 0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, and 50-60%. In addition, the combined ranges 0-20%, 20-40%, 40-60%, and minimum bias bins are included. For the yields with respect to the reaction plane, the centralities presented are 0-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%. Finally, the R_{AA} versus nuclear path length result excludes the most central bin due to its smaller intrinsic ellipticity (the average path length is insensitive to $\Delta\phi$).

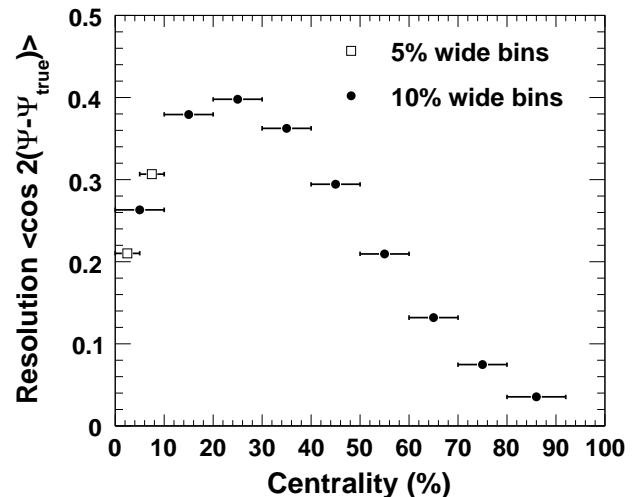


FIG. 1: Reaction plane resolution correction as a function of centrality.

B. Reaction plane determination

The technique used to determine the reaction plane on an event-by-event basis is the same used in previous PHENIX analyses [14, 40, 41]. The quartz radiators of each counter are arranged in approximately concentric circles around the beam axis. The light collected in the photo-multiplier tubes (PMTs) allows for an estimate of the number of charged particles passing through the detector.

The number of charged particles at a given PMT position, N_i , is weighted in a manner to reduce the bias of the inner rings and used to measure the orientation of the reaction plane from the formula

$$\tan(2\Psi) = \frac{\sum_i w_i N_i \sin(2\phi_i) - \langle \sum_i w_i N_i \sin(2\phi_i) \rangle}{\sum_i w_i N_i \cos(2\phi_i) - \langle \sum_i w_i N_i \cos(2\phi_i) \rangle}, \quad (1)$$

where ϕ_i is the nominal azimuth of the radiator. Subtraction of the average centroid removes biases due to various detector effects. A final flattening technique is used to remove the residual non-uniformities in the distribution of angles.

To estimate the resolution of the reaction plane measurement, we use the sub-event technique [42]. The approach consists of dividing the event up into two sub-events roughly equal in size. The two individual BBCs provide a natural sub-event division, so we analyze the distribution of event-by-event differences between the reaction plane angles measured in the north and south counters, $\Delta\Psi = \Psi_N - \Psi_S$. In the presence of pure flow, this distribution takes the form [42]:

$$\frac{dN}{d\Delta\Psi} = \frac{e^{-\chi^2}}{2} \left\{ \frac{2}{\pi}(1 + \chi^2) + z[I_0(z) + L_0(z)] + \chi^2[I_1(z) + L_1(z)] \right\}. \quad (2)$$

where $z = \chi^2 \cos(2\Delta\Psi)$ and the functions I_n and L_n are the modified Bessel functions of the first kind and modified Struve functions, respectively. The parameter χ describes the dispersion of the flow \vec{Q} vector and thus determines the correction required for the reaction plane resolution. Since $\Delta\Psi$ represents the whole-event difference distribution and we are dealing with sub-events with roughly half the multiplicity of the event, we replace $\chi \rightarrow \chi/\sqrt{2}$ in Eq. 2 and fit this function to the measured $\Delta\Psi$ distribution to extract χ . The resulting value is then used to evaluate the resolution of the event-plane of n^{th} order [42]:

$$\langle \cos n(\Psi - \Psi_{RP}) \rangle = \frac{\sqrt{\pi}}{2} \chi e^{-\frac{\chi^2}{2}} \left[I_{\frac{n-1}{2}} \left(\frac{\chi^2}{2} \right) + I_{\frac{n+1}{2}} \left(\frac{\chi^2}{2} \right) \right] \quad (3)$$

where the true reaction plane orientation is denoted by Ψ_{RP} and the observed orientation by Ψ . Figure 1 shows the resolution correction obtained using the above-described procedure as a function of centrality. Both 5% and 10% wide bins are shown for comparison.

Eq. 2 is derived under the assumption that the azimuthal distributions are free of non-flow effects. Due to the large rapidity gap between the BBCs and the central arm region, it is expected that particles observed in the BBCs have no correlation with those measured in the central arm detectors. PYTHIA [43] studies have been used to confirm that jets observed in the central arm have negligible effect on the reaction plane measurement from the BBCs[44].

C. Neutral pion measurement

Measurement of neutral pions has played a critical role in the study of high- p_T phenomena at RHIC, and especially by PHENIX [12, 19, 25]. The two-particle decay channel $\pi^0 \rightarrow \gamma + \gamma$ provides a clean signal of identified hadrons out to the highest p_T regions.

EMCal showers are found by clustering contiguous towers with energy above a threshold energy (10 MeV) and requiring at least 50 MeV in the tower with highest energy deposit. The impact position is calculated from the positions of the participating towers weighted by the logarithm of deposited energy. The energy of the cluster is corrected for non-perpendicular incidence – the angle being derived by assuming a straight path between the actual vertex and the calculated impact point – as well as nonlinearities [25]. In high-multiplicity events such as central Au + Au collisions, there is an increasing probability for clusters to overlap (one tower accumulates energy from more than one particle), which can distort an energy measurement from a simple sum over contiguous towers. To mitigate this effect, the EMCal clustering algorithm also provides a quantity called *ecore*, which is determined by extrapolating the “core” energy represented by the central four or five towers in the cluster, assum-

ing an electromagnetic shower profile. The energy- and impact angle- dependent shower profile is a model developed from and checked against beam test data. In this way, *ecore* provides a more realistic measurement of the shower energy, less prone to contributions from accidental overlaps (particles hitting close enough they deposit energy in the same towers) than a simple energy sum of participating towers would be. We use this *ecore* for the energy of reconstructed clusters in this analysis.

The invariant mass of a photon pair γ_i, γ_j as measured in the EMCal is calculated from the energy of the clusters and their measured position:

$$m_{\gamma_i\gamma_j} = \sqrt{(P_{\gamma_i}^2 + P_{\gamma_j}^2)} = \sqrt{2E_i E_j \cos(1 - \theta_{ij})} \quad (4)$$

where θ_{ij} is the opening angle between the two photons and $m_{\gamma_i\gamma_j}$ is equal to the π^0 mass for photons from the decay of the same π^0 . Since the photons from the π^0 are not tagged, such pairs have to be formed from each photon pair in the event where the pair momentum falls in a particular p_T bin, and some of these pairs might accidentally reproduce the π^0 mass as well (combinatorial background), particularly at lower p_T and higher centralities (multiplicities). Since π^0 s cannot be uniquely identified, raw π^0 yields are extracted statistically, by subtracting the combinatorial background from the invariant mass distribution.

A well-known technique to reduce the combinatorial background is to place a cut on the energy asymmetry of the pair, as defined by:

$$\alpha = \frac{|E_1 - E_2|}{E_1 + E_2} = \beta |\cos \theta^*|. \quad (5)$$

Because the angular distribution $d\sigma/d\cos\theta^*$ of the pairs in the rest frame of the π^0 is uniform, the asymmetry distribution should be flat. However, due to the steeply falling photon spectrum, fake (non-correlated) pairs which still give the proper π^0 mass are strongly peaked towards $\alpha = 1$. A pair of clusters in the EMCal is considered a neutral pion candidate only if the pair's

asymmetry is less than 0.8. In addition, the two photons are required to be separated by at least 8 cm for the combination to be considered as a π^0 candidate.

There remains a non-trivial background contribution which passes these cuts: pairs of photons from different π^0 s, or, more generally, from pairs of uncorrelated clusters which pass the photon identification cuts and accidentally give an invariant mass near the true π^0 mass. This remaining combinatorial background is estimated and subtracted using the event mixing method. The procedure involves forming pairs from different events, which will by definition be uncorrelated. Each photon candidate is combined with all the photon candidates in previous events stored in memory. In order to replicate the background from uncorrelated pairs within the same event as closely as possible in the mixed events, mixing is performed within bins of centrality, vertex z position, and reaction plane orientation. Since all events analyzed are minimum-bias, no special steps are needed to avoid the distortions of the mixed-event background by the trigger requirement. All cuts applied to the combinations of same event pairs are also applied to mixed-event pairs. The number of events buffered determines the statistics of the event-mixed distributions, chosen as a tradeoff between desired statistical accuracy and computational resources. The data presented in this article are mixed with five previous events (in each centrality, vertex, and reaction plane bin).

For a given p_T bin, the mixed-event mass distribution is normalized to the same-event distribution in a region away from the π^0 mass peak. The normalization region is 0.25–0.45 GeV/ c^2 for $p_T < 6.0$ GeV/ c and 0.21–0.45 GeV/ c^2 otherwise. Fig. 2 shows an example of this subtraction process for two p_T ranges in two centrality bins.

The scaled background distribution is then subtracted from the same-event pair distribution. The subtracted result thus represents a sample of real π^0 s. The peak is fit to a Gaussian to determine its width and mean position. The raw yield of π^0 s is determined by integrating the counts in a window of $\pm 2\sigma$ around the mean. The width and mean are recorded and parameterized as a function of p_T and centrality based upon this ϕ -integrated, large sample. The positions and widths from this parameterization are then used when we extract the (much smaller) raw yields in bins of angle $\Delta\phi$ with respect to the reaction plane. The maximum variation of the yields (multiplicities) with $\Delta\phi$ is only about a factor of 2, and therefore the means and widths are not expected to change substantially. Furthermore, the statistics are much poorer in the $\Delta\phi$ bins, which would make individual π^0 fits unreliable.

There is a residual background in the invariant mass distributions even after the mixed-event distribution has been removed, especially at lower p_T (below ~ 2 GeV/ c). This is due to correlations that event mixing cannot reproduce, like the “sub-event structure” due to the presence of jets or multiple, close-by showers from an annihilating anti-neutron, or imperfections of the reconstruc-

tion algorithm, such as cluster merging, cluster splitting, and a host of other contributions. Much of the residual background is excluded by starting the fit at 0.09 GeV/ c . What is left is accounted for by including a first-order polynomial in the fits to the (already background-subtracted) invariant mass distribution, and subtracting its integral from the raw π^0 yield (see Fig. 2). In the more central events, the peak deviates slightly from gaussian on the high mass side, due to overlapping clusters. The use of *ecore* mitigates this effect, and the systematic uncertainty on yield extraction arising from the remaining asymmetry has been estimated to be 3–4% [19].

D. Elliptic flow measurement

To obtain the azimuthal angle dependence of π^0 production, we measure raw π^0 yields in a given p_T bin as a function of the π^0 angle with respect to the reaction plane orientation in six equally-spaced bins of $\Delta\phi = \phi(\pi^0) - \Psi_{RP}$ covering the range $0 < \Delta\phi < \pi/2$. The π^0 yields are measured in each $\Delta\phi$ bin using the same procedure described in III C for the reaction-plane inclusive measurement except that the mass fits are not performed in each $\Delta\phi$ bin. Instead, the peak integration window is set $\pm 2\sigma$ around the mean where the width and mean are taken from the inclusive analysis. The resulting raw π^0 angular distribution $dN/d\Delta\phi$ can then be fit to determine the strength of the modulation in the yield. Because the PHENIX BBCs have uniform azimuthal coverage, the π^0 measurements have uniform acceptance in $\Delta\phi$ when averaged over a large event sample, despite the limited azimuthal acceptance of the PHENIX electromagnetic calorimeters.

Assuming elliptic flow is the dominant source of $\Delta\phi$ variation in the π^0 yields, we perform a fit to the angular distributions of the form

$$\frac{dN}{d\Delta\phi} = N_0(1 + 2v_2^{\text{meas}} \cos 2\Delta\phi). \quad (6)$$

We use an analytic linear χ^2 fitting procedure that matches the integral of Eq. 6 over each of the $\Delta\phi$ bins to the measured π^0 yield within the corresponding bin. In the definition of the χ^2 function we account for non-zero covariances between the yields in the different $\Delta\phi$ bins resulting from the limited acceptance of the calorimeters. These covariances have been evaluated separately for each p_T and centrality bin. Examples of the raw $dN/d\Delta\phi$ distributions and the results of the χ^2 fits are shown in Fig. 3. The resulting v_2^{meas} values are then corrected upward to account for reaction plane resolution using correction factors described in Section III B.

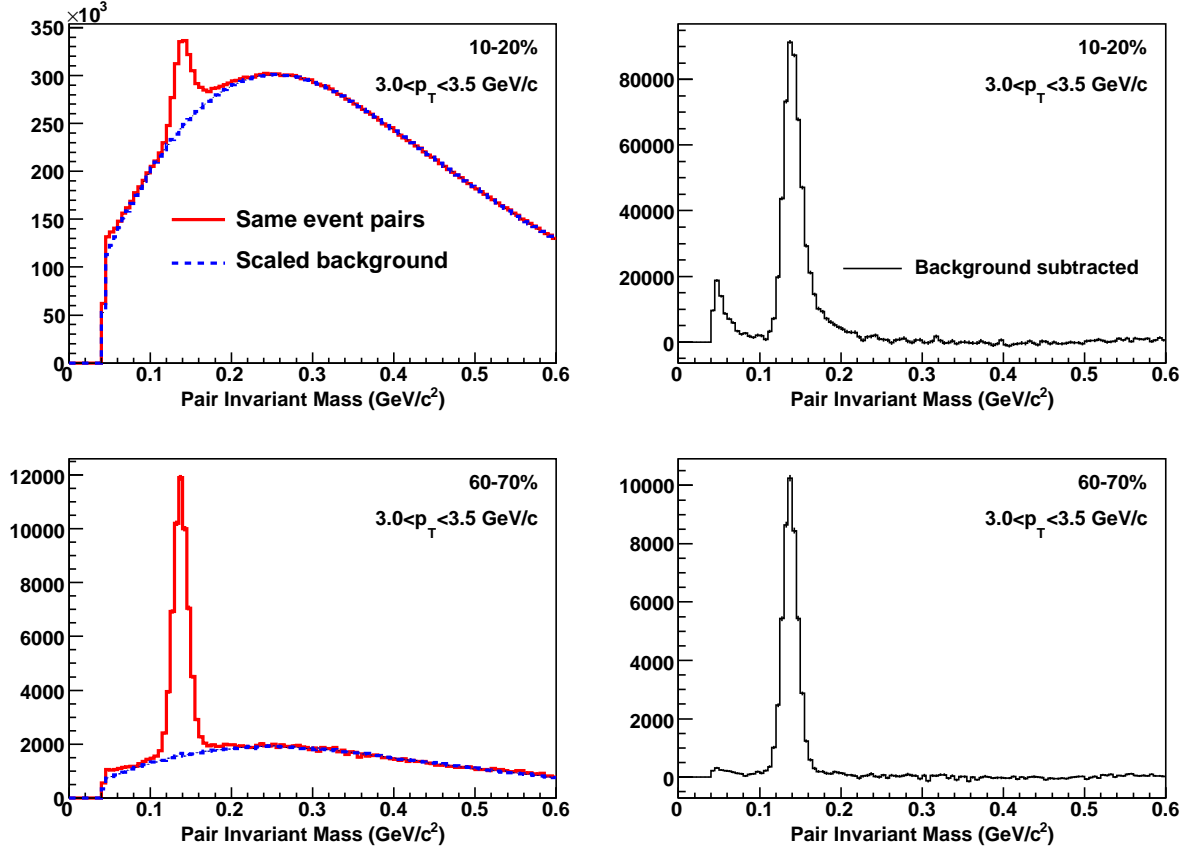


FIG. 2: Invariant mass distributions at moderate p_T and two different centralities. Left panels: same event and normalized mixed event distributions. Right panel: the subtracted distributions, which are then fitted with the sum of a first degree polynomial and a Gaussian.

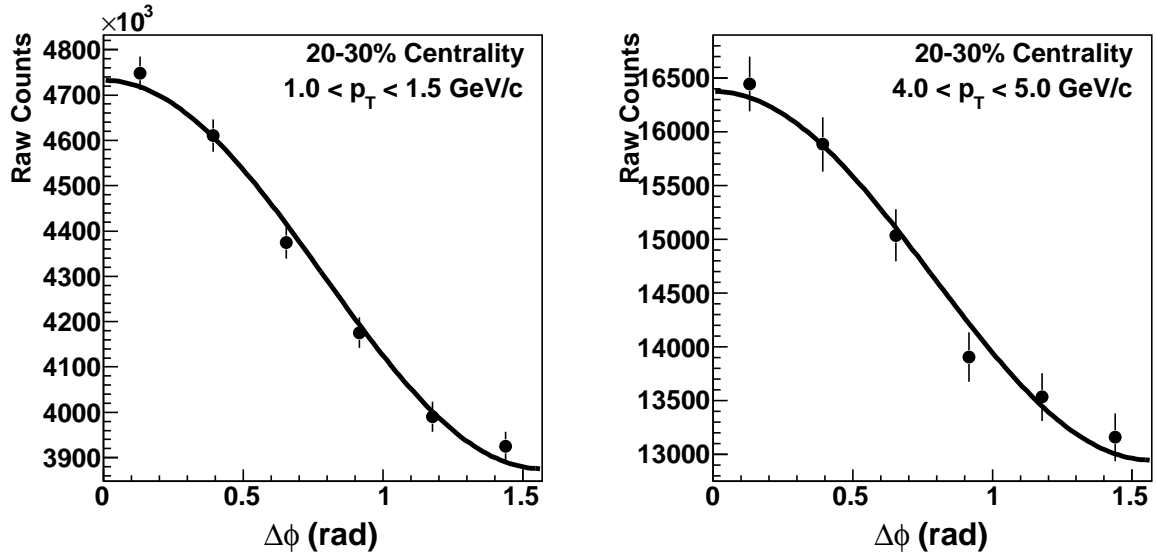


FIG. 3: Example of analytic fitting of raw $dN/d\Delta\phi$ distributions

E. $R_{AA}(\Delta\phi)$ measurement

The nuclear modification factor R_{AA} has played a critical role in understanding energy loss mechanisms. R_{AA} is defined as

$$R_{AA}(p_T) = \frac{(1/N_{AA}^{evt})d^2N_{AA}^{\pi^0}/dp_T dy}{\langle T_{AA} \rangle \times d^2\sigma_{pp}^{\pi^0}/dp_T dy} \quad (7)$$

where $\langle T_{AA} \rangle$ is the mean Glauber overlap function for the centrality being analyzed:

$$\langle T_{AA} \rangle \equiv \frac{\int T_{AA}(\mathbf{b})d\mathbf{b}}{\int (1 - e^{-\sigma_{pp}^{inel} T_{AA}(\mathbf{b})})d\mathbf{b}}, \quad (8)$$

from which the mean number of binary nucleon-nucleon collisions can be calculated, $\langle N_{coll} \rangle = \sigma_{pp}^{inel} \langle T_{AA} \rangle$.

For each p_T bin, we can calculate the ratio

$$R(\Delta\phi_i, p_T) = \frac{N(\Delta\phi_i, p_T)}{\sum_{i=1}^6 N(\Delta\phi_i, p_T)} \quad (9)$$

where $N(\Delta\phi_i, p_T)$ is the number of π^0 s observed in the given $(\Delta\phi_i, p_T)$ bin. Since the BBC is azimuthally symmetric the PHENIX acceptance has no $\Delta\phi$ dependence, there should be no azimuthal dependence to efficiency and acceptance corrections. As a result,

$$R_{AA}(\Delta\phi_i, p_T) = R(\Delta\phi_i, p_T) \times R_{AA}(p_T). \quad (10)$$

Thus, we can use measured inclusive $R_{AA}(p_T)$ to convert $R(\Delta\phi_i, p_T)$ to $R_{AA}(\Delta\phi_i, p_T)$. Since the detector efficiency and acceptance corrections are already contained in $R_{AA}(p_T)$, there is no need to apply them to $R(\Delta\phi_i, p_T)$.

Prior to calculating $R_{AA}(\Delta\phi_i, p_T)$ we correct the ratios $R(\Delta\phi_i, p_T)$ for the finite reaction plane resolution using an approximate unfolding technique. For a pure flow $\Delta\phi$ distribution, we can express the influence of the resolution broadening on the measured $\Delta\phi$ distribution

$$R^{\text{meas}}(\Delta\phi_i, p_T) = R^{\text{true}}(\Delta\phi_i, p_T) \left[\frac{1 + 2v_2^{\text{meas}} \cos(2\Delta\phi)}{1 + 2v_2^{\text{corr}} \cos(2\Delta\phi)} \right], \quad (11)$$

where according to the results of Section III B $v_2^{\text{meas}} = v_2^{\text{corr}} / \langle \cos 2(\Psi - \Psi_{RP}) \rangle$. Then, if the measured $\Delta\phi$ distribution resulted from pure elliptic flow, it could be corrected back to the true distribution by

$$R^{\text{corr}}(\Delta\phi_i, p_T) = R^{\text{meas}}(\Delta\phi_i, p_T) \left[\frac{1 + 2v_2^{\text{corr}} \cos(2\Delta\phi)}{1 + 2v_2^{\text{meas}} \cos(2\Delta\phi)} \right]. \quad (12)$$

As shown above, the general features of the measured π^0 $\Delta\phi$ distributions are well-described by pure $\cos(2\Delta\phi)$ modulation. However, we wish to preserve in our measurements of the azimuthal dependence of the π^0 production the full shape of the measured $\Delta\phi$ distribution, including possible small non-elliptic contributions. For this purpose, the correction described in Eq. 12 applied

to the data represents an approximation to a full unfolding procedure that becomes exact when the distribution is purely $\cos(2\Delta\phi)$ in form. We have checked for a few cases that a full unfolding procedure applied to the measured $dN/\Delta\phi$ distributions using singular value decomposition regulation of the response matrix reproduces the correction in Eq. 12. From the corrected ratios, $R^{\text{corr}}(\Delta\phi_i, p_T)$, we use Eq. 10 to obtain $R_{AA}(\Delta\phi_i, p_T)$.

IV. RESULTS

A. Elliptic flow coefficient

The results of the v_2 measurements using the methods described in Sec. III D are presented in Fig. 4 as a function of p_T for different centrality bins. The data points in the figure are plotted at the mean π^0 p_T in bins of width $\Delta p_T = 0.5$ GeV/c for $p_T < 4$ GeV/c and $\Delta p_T = 1$ GeV/c for $p_T > 4$ GeV/c. The error bars shown on the v_2 data points were obtained by multiplying the raw v_2 fit errors (see Section III D) by the same reaction plane resolution correction factor applied to the v_2 values themselves. The error bars, then, represent uncorrelated statistical errors on the measured v_2 values arising from statistical errors on the $dN/d\Delta\phi$ data points used in the fits (these errors would be categorized as Type A uncertainties in the framework described in [45] or p_T -uncorrelated). Systematic errors on the v_2 measurements due to the reaction plane determination procedure and from systematic uncertainties in the reaction plane resolution correction are represented in Figs. 4,5 by filled boxes, which for most data points are similar in size or smaller than the data points (these uncertainties are classified as Type B [45] or p_T -correlated).

Figure 5 shows $v_2(p_T)$ for four centrality ranges, obtained by combining data from the centrality bins shown in Fig. 4. The corrected $dN/d\Delta\phi$ distributions from individual centrality bins were summed over a given centrality range and then fit to obtain the corrected v_2 values shown in Fig. 5. The reaction plane resolution correction produces correlated errors in the corrected $dN/d\Delta\phi$ distributions for each original centrality bin, and these correlated errors persist in the summed $dN/d\Delta\phi$ distribution. These correlated errors are not included in the statistical errors for the fit to the combined $dN/d\Delta\phi$ distribution, but their impact on the final v_2 value is estimated separately by evaluating the changes in the v_2 fit parameter that result from adding to the summed $dN/d\Delta\phi$ values $\pm 1 \sigma$ of the correlated errors. Since this estimated uncertainty results from the statistical uncertainties on the v_2 values for the original centrality bins, we include the 1σ bounds obtained from this procedure in the statistical error on the v_2 values for the combined centrality bins. Systematic errors for the combined bins are plotted similarly to those in Fig. 4.

The results presented here nearly double the p_T range of previous PHENIX π^0 v_2 measurements from RHIC

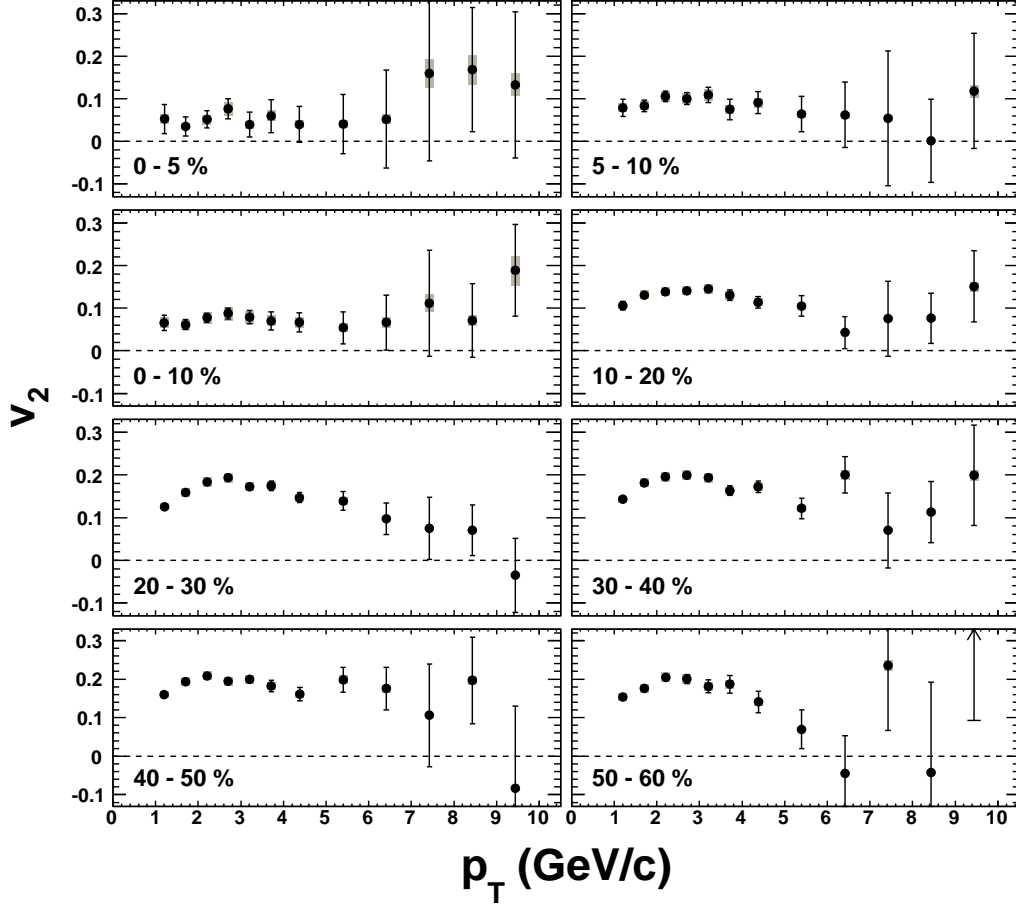


FIG. 4: π^0 v_2 versus p_T for centralities 0-5%, 5-10%, 0-10%, 10-20%, 20-30%, 30-40%, 40-50%, and 50-60%. The arrow in the 50-60% panel shows the lower limit of the uncertainty on the data point, which lies outside the bounds of the plot.

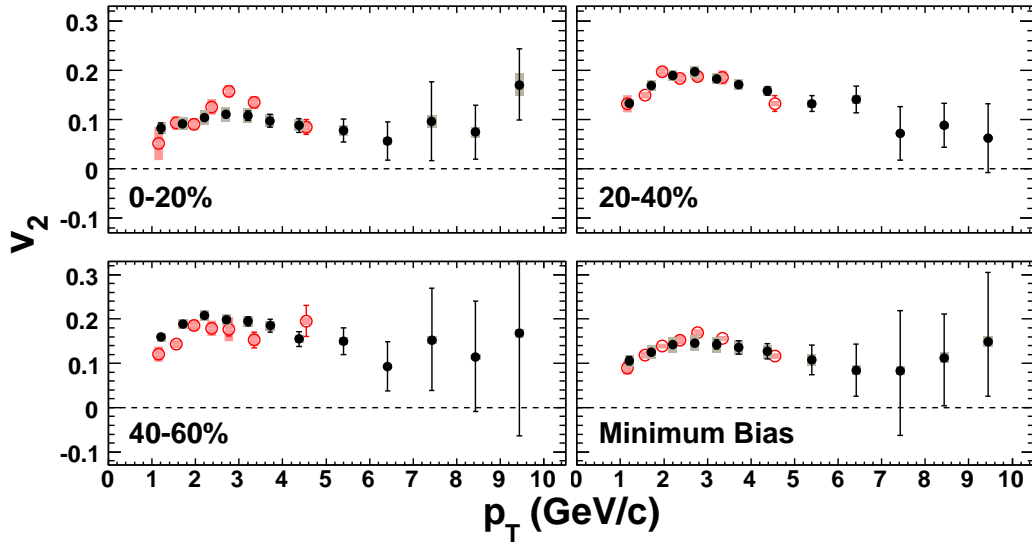


FIG. 5: (Color online) π^0 v_2 versus p_T for centralities 0-20%, 20-40%, 40-60%, and minimum bias. The closed (black) circles are data presented in this paper, and the open (red) circles are previously published results [40].

Run-2 [40]. Those measurements are shown for comparison purposes in Fig. 5. Good agreement is seen between the Run-4 measurements presented here and the Run-2 results except in the 40-60% centrality bin where the new v_2 measurements are systematically higher by $\sim 30\%$. This difference is attributed to improved reaction plane resolution corrections for the 40-60% centrality bin resulting from the combining of *corrected* $dN/\Delta\phi$ distributions from smaller centrality bins. This summing procedure better handles the rapid variation of reaction plane resolution with centrality in mid-central to peripheral collisions. Furthermore, we have cross-checked the procedure using 5% bins, verifying the combined result reproduces the data analyzed in wider bins. The previous Run 2 analysis did not have a sufficiently large data sample to allow the use of separate 40-50% and 50-60% bins, and therefore the reaction plane resolution correction was necessarily less accurate. The measured v_2 values presented in Fig. 4 and Fig. 5 are also consistent with previously published PHENIX charged pion v_2 measurements [14, 40].

The results in Figures 4 and 5 show a rapid increase of v_2 with increasing p_T at low p_T , a maximum in the range $2 < p_T < 3$ GeV/c, and then at higher p_T a decrease of v_2 with increasing p_T . An increase in v_2 at low p_T is well-established [46, 47, 48] and is understood to result from the collective elliptic flow of the medium generated by the initial spatial anisotropy of the collision zone. Hydrodynamical models have been successful in quantitatively describing the pion $v_2(p_T)$ in the region $p_T < 1.5$ GeV/c. However, it has also been well-established that the pion $v_2(p_T)$ deviates from the hydrodynamic prediction above 1.5 GeV/c, a result that is understood to imply the contribution of hard processes, distortions of the spectrum due to recombination at freeze-out, and/or effects from dispersive hadronic evolution after freeze-out. Thus, a change in the variation of v_2 with p_T near $p_T \sim 2$ GeV/c is not unexpected. If the large v_2 values at lower p_T are interpreted as resulting from soft, collective mechanisms, then a decrease in v_2 for $p_T > 3$ GeV/c suggested by the data in Fig. 4 would naturally reflect an increasing contribution of hard processes with smaller v_2 .

To statistically test the significance of the decrease of v_2 with p_T , we show in Fig. 6 the results of linear fits to the high- p_T v_2 values for the 20-30% and 30-40% centralities. The panels on the left-hand side of Fig. 6 display a series of fits beginning at higher p_T values, the first fit starting at the p_T near the maximum v_2 , $p_T = 2.5$ GeV/c. The right-hand panels show the $1\text{-}\sigma$ limits of the functions for the three fits in the series, calculated from the $1\text{-}\sigma$ variation of the two fit parameters (and including the covariance between them). The results of the fits indicate that the decrease of v_2 with p_T at higher p_T is statistically significant, though the data points for $p_T > 5$ GeV/c are not sufficient by themselves to establish a trend. We can state, however, that the points for $p_T > 5$ GeV/c are consistent with the linear decrease obtained including the lower p_T points. A question we would like to

answer, then, is whether the data show any indications of deviation from a monotonic decrease in $v_2(p_T)$ indicating the transition to a quenching-dominated azimuthal variation.

A complete understanding of $v_2(p_T)$ over the measured p_T range therefore requires the treatment of the transition from soft to hard dominated physics. According to the above discussion, in the p_T range where v_2 is maximum, particle production is likely not dominated by hard processes and the reduction of v_2 with increasing p_T indicates increasing hard-scattering contributions (or decreasing soft contamination). Motivated by this general argument, we have attempted to describe the results in Figs. 4 and 5 by a functional form

$$v_2(p_T) = \left(\frac{(p_T/\lambda)^m}{1 + (p_T/\lambda)^m} \right) \left(a + \frac{1}{p_T^n} \right). \quad (13)$$

The first term is intended to describe a rapidly rising and saturating soft v_2 resulting from collective motion while the second term represents a rapidly falling soft/hard ratio. The additive constant in the second term represents an asymptotic v_2 that could describe a constant or slowly varying azimuthal-dependent quenching. We show in Figs. 7-8 the optimum fits to the full set of $v_2(p_T)$ values in the different centrality bins and the result of 1σ variation of the fit parameters taking into account the complete covariance matrix from the fits.

The fits to the data show that the measured p_T dependence of the π^0 v_2 is qualitatively compatible with a description of the of low and intermediate p_T region in terms of a collective flow modulation diluted by a decreasing relative soft contribution with increasing p_T . Assuming this picture, it is then important to determine at what p_T the contamination from the soft production no longer dominates the measured $\Delta\phi$ variation of π^0 yield. For most of the centrality bins, the fits suggest that v_2 decreases over most of the measured p_T range albeit with a decreasing slope at higher p_T . The central bins are compatible with v_2 continuing to decrease beyond the measured p_T range although the 1σ uncertainty bands also accommodate v_2 saturating within the measured range. The more peripheral bins (30-40% and 40-50%) suggest that the v_2 has reached a nearly p_T independent value by ~ 5 GeV/c. The 50-60% centrality bin has sufficient fluctuations that little can be inferred from the p_T dependence of v_2 in that centrality bin. In all of the centrality bins, the data are consistent with a smooth reduction of $v_2(p_T)$ from a maximum to a non-zero value at high p_T with that value increasing in more peripheral collisions as would be expected from quenching in an increasingly anisotropic medium. While the functional form in Eq. 13 can describe the p_T variation of v_2 within the range of the current data and within the statistical fluctuations of the data points, it is possible that this description will fail at higher p_T with improved statistics. In fact, a statistically significant deviation of $v_2(p_T)$ from the form in Eq. 13 might provide the most direct evidence of the dominance of quenching effects in

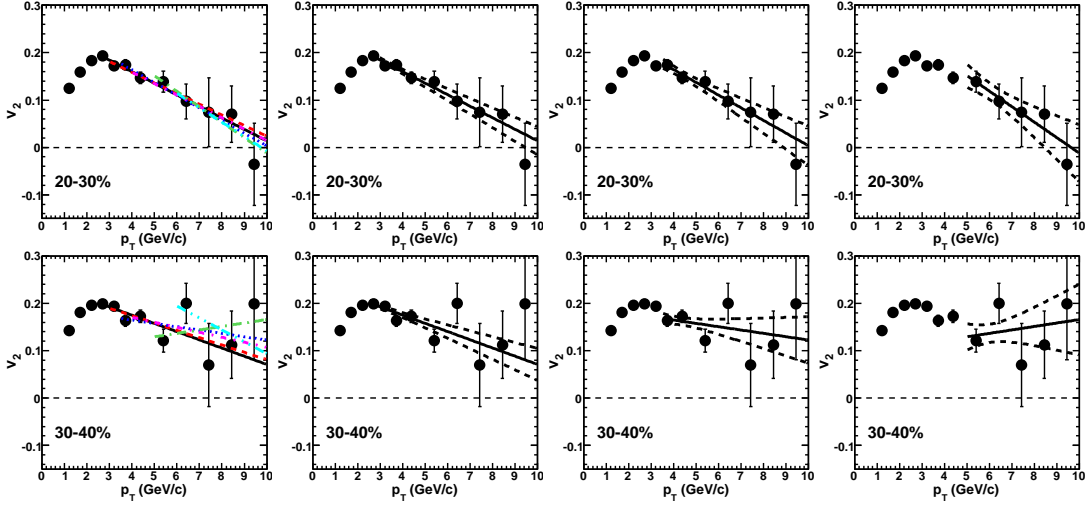


FIG. 6: (Color online) v_2 versus p_T for 20-30% and 30-40% centralities, with fits of the high- p_T data to a first order polynomial. From right to left, the first panel shows the series of fits, with each fit starting with a successively higher p_T . The second, third, and fourth panels show selected fits with uncertainty bands based on the $1\text{-}\sigma$ variation of the fit parameters, including their covariance.

determining v_2 .

B. Nuclear modification factor with respect to the reaction plane

The nuclear modification factor as a function of $\Delta\phi$ for six centrality bins is shown in Figs. 9-14. The closed circles represent the $\Delta\phi$ -dependent measurements described in this paper while the open circles positioned at $\Delta\phi = \pi/4$ represent the inclusive R_{AA} measurement [19]. In both cases statistical uncertainties (i.e. Type A) are represented by the error bars. For the inclusive R_{AA} measurement, the total systematic uncertainties (or Type C [45]) are shown by the boxes. The upper and lower 1σ ranges of the correlated statistical uncertainties (i.e. Type B) on the $R_{AA}(\Delta\phi)$ measurements resulting from the reaction plane resolution correction are shown by the (blue) solid and (red) dashed lines. For all bins except the 0-10% centrality bin a dotted line is plotted at $R_{AA} = 1$ for reference. We note that by construction, the average $R_{AA}(\Delta\phi)$ from the reaction plane dependent measurements must be equal to the inclusive R_{AA} .

The results in the Figs. 9-14 show that the in-plane π^0 suppression is generally weaker and varies more rapidly with p_T than the suppression for π^0 s produced at larger angles. As the collisions become more peripheral (for example, 50-60%), the small suppression seen in the inclusive R_{AA} almost vanishes for π^0 s emitted close to the reaction plane. In a previous analysis [25], it was observed that the in-plane R_{AA} even exceeded unity for peripheral collisions; these data exhibit no such enhancement. However, the results presented in this article agree within systematic errors with previously reported data.

The $R_{AA}(\Delta\phi)$ results are combined in Fig. 15 that shows the p_T dependence of the R_{AA} in each of the six $\Delta\phi$ bins included in this analysis. We use a semi-log scale so that the reduction of the $\Delta\phi$ -integrated R_{AA} in more

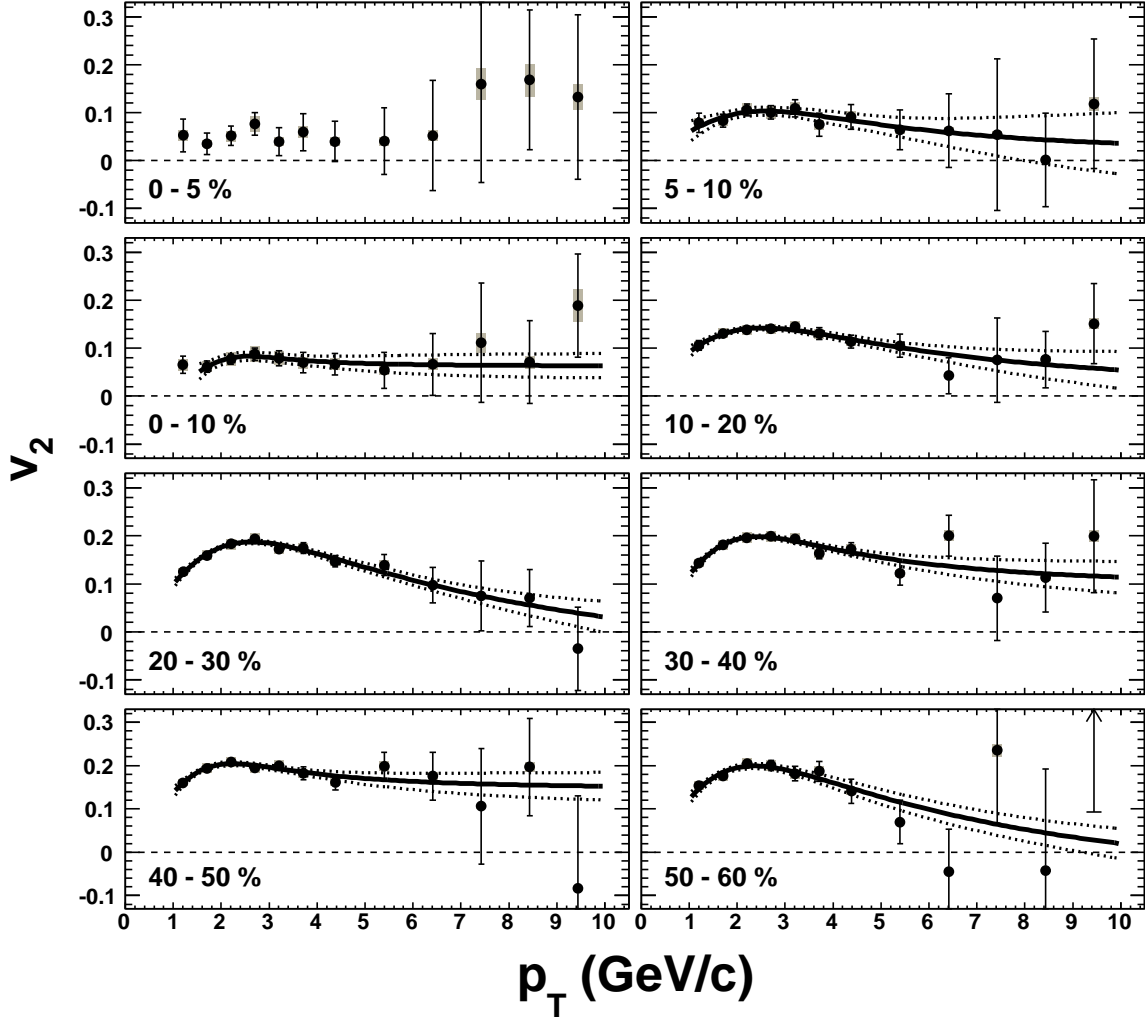


FIG. 7: π^0 v_2 versus p_T for centralities 0-5%, 5-10%, 0-10%, 10-20%, 20-30%, 30-40%, 40-50%, and 50-60%. The arrow in the 50-60% panel shows the lower limit of the uncertainty on the data point, which lies outside the bounds of the plot. The solid lines represent the fit to the data, Eq. 13. The dashed lines represent the 1σ deviations of the fit function. See text for more details.

central collisions does not confuse the interpretation of the results. For clarity, the results from the 20-30%, 30-40%, 40-50%, and 50-60% centrality bins are shown on linear plots in Fig. 16.

The $R_{AA}(p_T)$ results exhibit a peak near 2 GeV/c, which becomes more prominent for more central collisions. The peak is strongest in the 0-10% bin where there is little modulation of the $\Delta\phi$ distributions at low or high p_T , so the peak cannot be directly attributed to elliptic flow. The peak in R_{AA} near 2 GeV/c is much weaker in the more peripheral (40-50% and 50-60%) centrality bins, particularly for π^0 s produced at larger $\Delta\phi$, and the primary variation seen in these peripheral bins with increasing $\Delta\phi$ is a reduction in R_{AA} that is only weakly p_T dependent.

For the intermediate centrality bins (10-20% through 30-40%) the peaking in R_{AA} is seen in all $\Delta\phi$ bins, but

is much stronger in the in-plane bins. For these intermediate centralities and for p_T values above the peak in R_{AA} ($p_T \gtrsim 3$ GeV/c), the R_{AA} for π^0 s produced at angles normal to the reaction plane is nearly constant with p_T while the R_{AA} for π^0 s produced at small angles from the reaction plane decreases rapidly with increasing p_T . The near constancy of the out-of-plane R_{AA} together with the rapid reduction in in-plane R_{AA} indicates that in the intermediate centrality bins, the v_2 and inclusive R_{AA} decrease simultaneously with increasing p_T such that $R_{AA}(\pi/2, p_T) = R_{AA}(p_T)(1 - 2v_2)$ is approximately constant. We will argue below that a correlation between R_{AA} and v_2 may naturally result from the underlying physics responsible for the azimuthal variation of the particle yields. However, we observe that a simultaneous reduction in integrated R_{AA} and v_2 suggested by the more central $R_{AA}(p_T)$ data would be contrary to

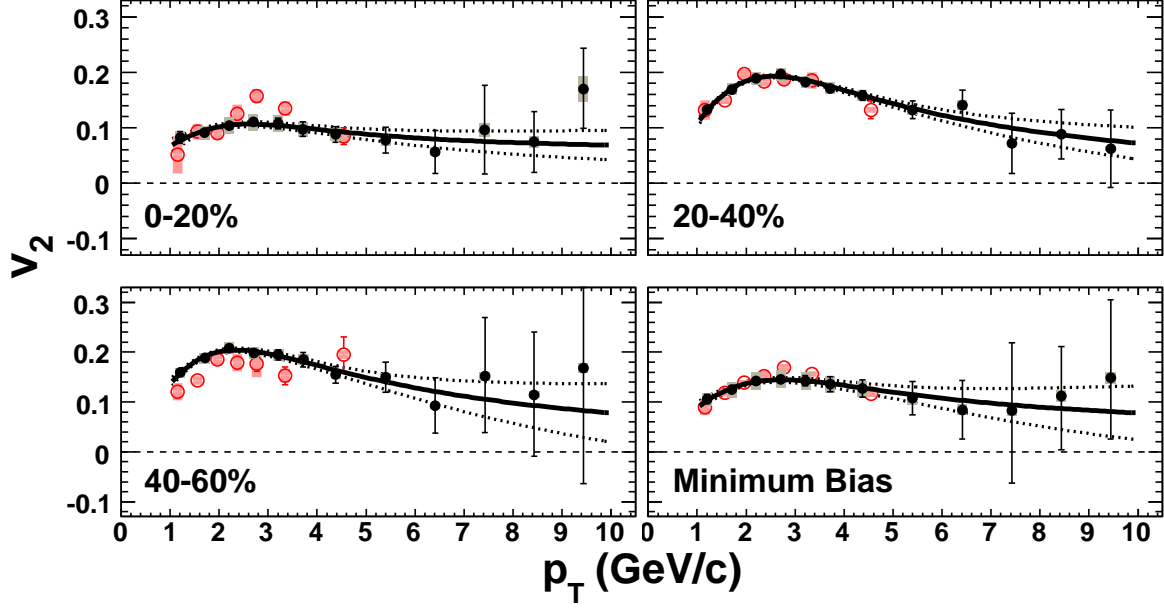


FIG. 8: (Color online) π^0 v_2 versus p_T for centralities 0-20%, 20-40%, 40-60%, and minimum bias. The closed (black) circles are data presented in this paper, and the open (red) circles are previously published results [40]. The solid and dashed lines as in Fig. 7.

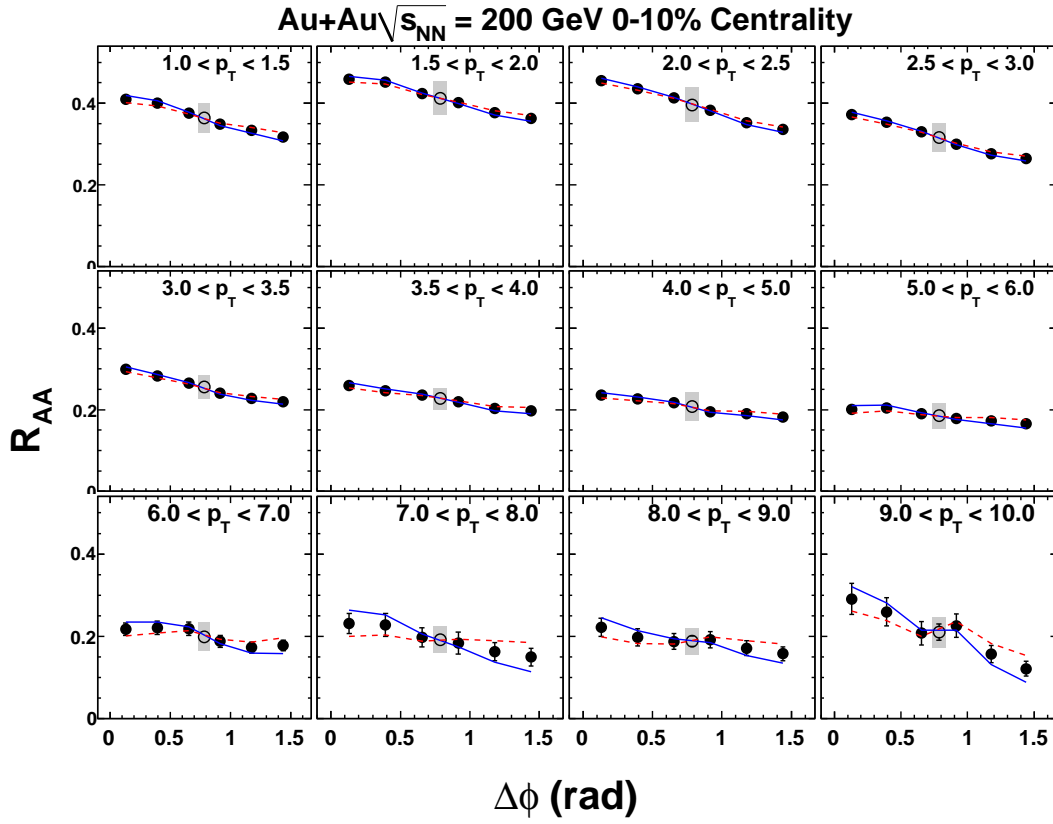


FIG. 9: (Color online) π^0 R_{AA} versus angle of emission with respect to the reaction plane for 0-10% centrality. The error bars denote the statistical errors, while the solid (blue) line and dashed (red) line represent the systematic error due to the resolution correction factor. The inclusive R_{AA} measurement is shown with the open circle, for which the error bar shows the statistical error and the box shows the systematic error.

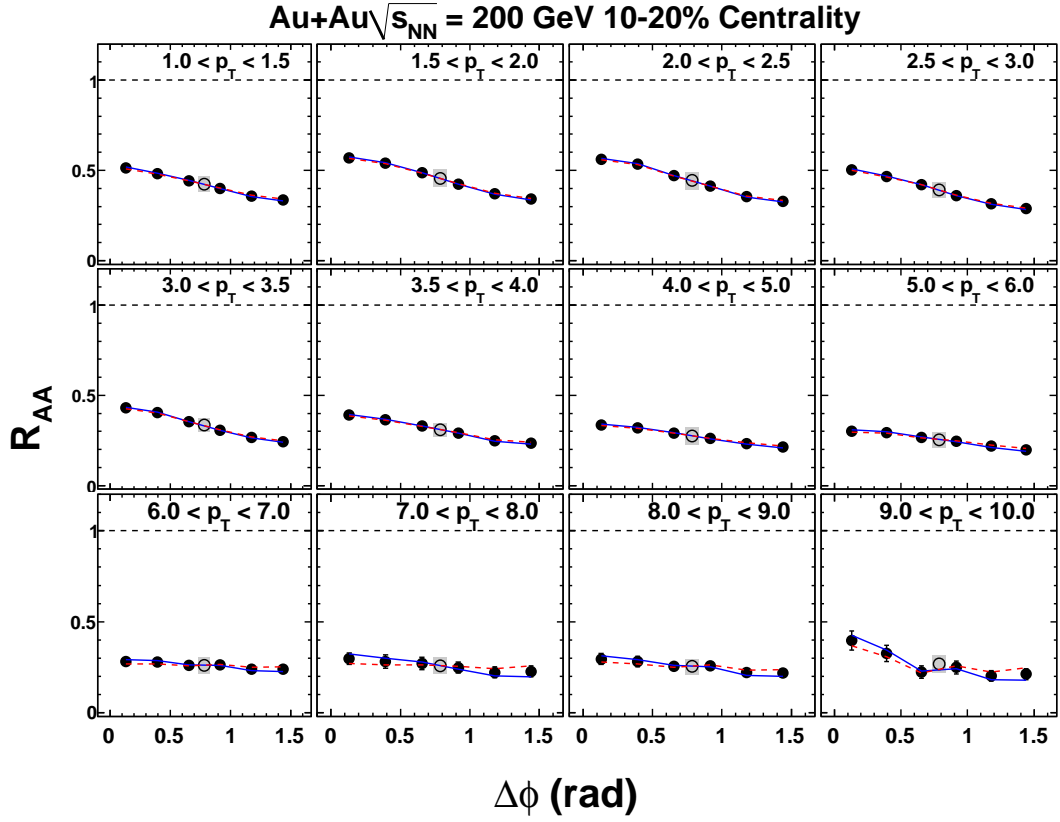


FIG. 10: π^0 R_{AA} versus angle of emission with respect to the reaction plane for 10-20% centrality. Colors/data points as in Fig. 9.

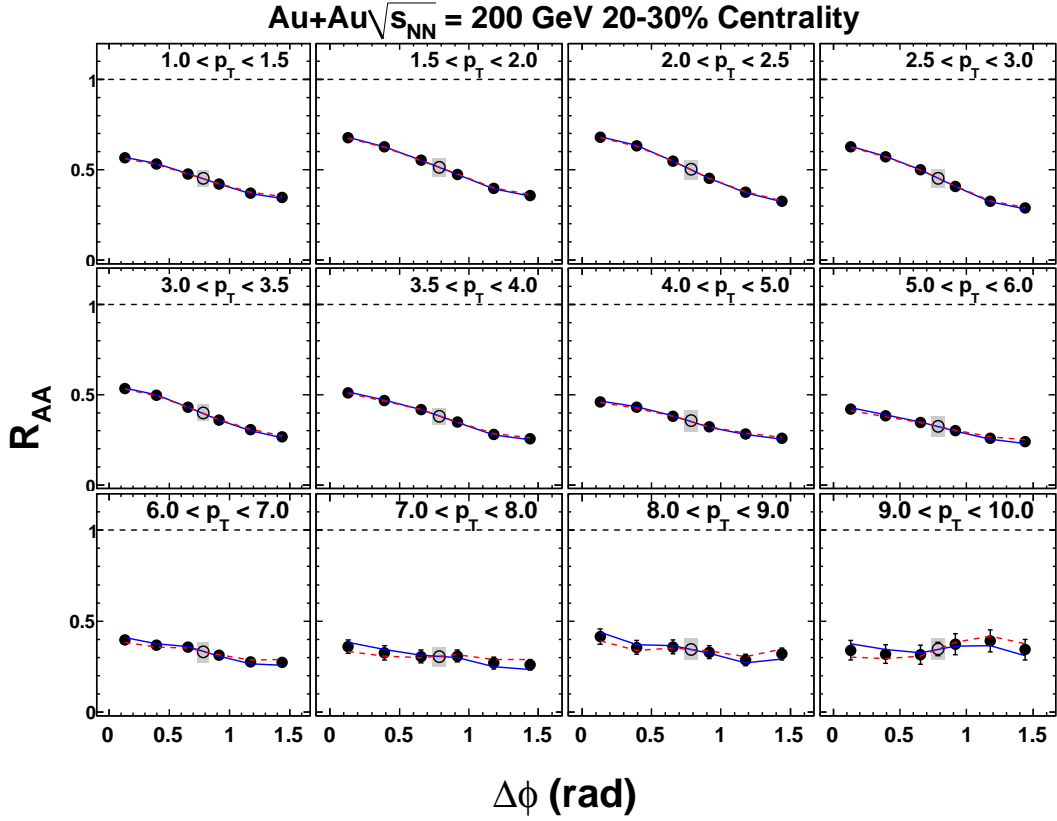


FIG. 11: π^0 R_{AA} versus angle of emission with respect to the reaction plane for 20-30% centrality. Colors/data points as in Fig. 9.

naive energy loss expectations since smaller R_{AA} would imply stronger quenching in the medium which would, in turn, imply larger variation between in-plane and out-of-plane quenching.

A similar implicit correlation between integrated R_{AA} and v_2 is seen in the centrality dependence of the $R_{AA}(\Delta\phi)$ results. These are re-plotted in Fig. 17 as a function of N_{part} for three $\Delta\phi$ bins – the bins closest to and further from the reaction plane and one of the intermediate bins. For $N_{part} > 100$, the out-of-plane R_{AA} values are nearly independent of centrality while the in-plane R_{AA} values decrease rapidly with increasing centrality. This result would have a natural geometric interpretation for π^0 production dominated by hard scattering and jet quenching. The length of the medium normal to the reaction plane varies only slowly with centrality except in the most peripheral collisions. Then, if the π^0 suppression is determined primarily by the path length of its parent parton in the medium, the π^0 R_{AA} would be nearly constant. Following the same argument, the yield for pions in the direction of the reaction plane would be much less suppressed in non-central collisions due to the short path lengths of the parent partons in the medium. However, with increasing centrality and decreasing anisotropy of the collision zone, the in-plane parton path lengths would grow to match those in the out-

of-plane direction. Thus, if the π^0 suppression depended primarily on path length, the in-plane R_{AA} would naturally drop to match the out-of-plane values reproducing the behavior of Fig. 17. In order to better see the difference between the in- and out-of-plane behaviors, these data are also plotted on Fig. 18 with a semi-log scale.

One difficulty with this geometric interpretation of the $R_{AA}(\Delta\phi)$ results given above is that the trend in the data that it is supposed to explain persists down to low p_T , where the v_2 values are too large to be accounted for via perturbative or formation time based energy loss scenarios [26, 27, 28, 29, 30, 49]. That fact coupled with the pronounced peaking in $R_{AA}(\Delta\phi)$ near 2 GeV/c suggests that physics other than hard scattering and jet quenching must be invoked to explain the π^0 yields at intermediate p_T . However, the fact that the out-of-plane yields show less pronounced peaking near 2 GeV/c, that they vary little as a function of p_T above 3 GeV/c, and that they vary little with centrality for $N_{part} > 100$ could be interpreted to imply that the π^0 suppression at angles normal to the reaction plane more directly represents the effects of quenching of hard quarks and gluons while the yield of π^0 s produced more closely aligned with the reaction plane is enhanced by the collective motion of the system. That additional enhancement could either be due to soft hadrons being boosted to larger p_T values by the collec-

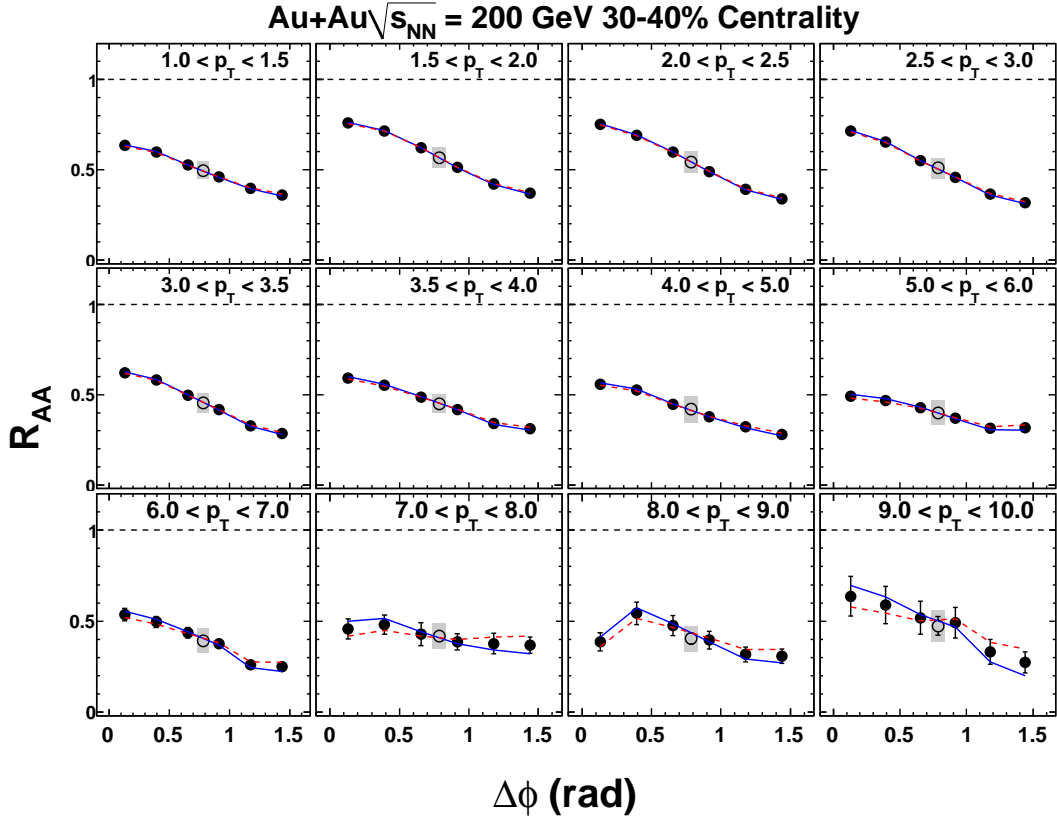


FIG. 12: π^0 R_{AA} versus angle of emission with respect to the reaction plane for 30-40% centrality. Colors/data points as in Fig. 9.

tive elliptic flow or could result from weaker quenching for partons moving in the direction of the flow field [27, 50]. Simultaneous description of the in-plane and out-of-plane behavior is a sensitive test of energy loss models.

The v_2 values presented in Figs. 7-8 also peak near 2 GeV/c, but the locations of the maxima in v_2 are shifted to higher p_T than the maxima in $R_{AA}(\Delta\phi)$. This suggests that the two effects may not directly related, but we observe that the maxima in the $R_{AA}(p_T)$ distributions in Figs. 15-16 shift to larger p_T for smaller $\Delta\phi$. To better illustrate the shift of the maxima in $R_{AA}(p_T)$ we show in Fig. 19 the $R_{AA}(p_T)$ values for the different $\Delta\phi$ bins and indicate the variation of the peak position obtained using polynomial fits to the first four p_T bins. For the 30-40% centrality bin, the maximum in $R_{AA}(p_T)$ for $\Delta\phi < \pi/12$ is shifted by 0.4 GeV/c relative to the $5\pi/12 < \Delta\phi < \pi/2$ bin. This shift in the peak $R_{AA}(p_T)$ with $\Delta\phi$ can produce a $v_2(p_T)$ that peaks higher in p_T than the inclusive R_{AA} .

The observed shift in the peak of $R_{AA}(p_T)$ with $\Delta\phi$ illustrates an important property of collective motion of the medium. The collective motion does not simply superimpose azimuthal variation on the particles produced at a given p_T , it provides a $\Delta\phi$ dependent shift and/or broadening in the transverse momentum spectrum of the produced particles. The resulting distortion will be the

smallest for particles produced at angles normal to the reaction plane and will be largest for particles produced in the plane. Any collective shift of soft particles to higher p_T will increase the measured $R_{AA}(\Delta\phi, p_T)$ for small $\Delta\phi$ relative to large $\Delta\phi$ values producing a simultaneous increase in both the $\Delta\phi$ -integrated R_{AA} and the v_2 . With increasing p_T , an expected decrease in the soft contamination would naturally explain the simultaneous reduction in v_2 and $\Delta\phi$ -integrated R_{AA} evident in the 10-20% and 20-30% bins where the separation between the $R_{AA}(p_T)$ curves for different $\Delta\phi$ bins decreases while the average R_{AA} also decreases. We will return to investigate this correlation again below.

The 40-50% and 50-60% centrality bins in Fig. 15 show little of the peaking near 2 GeV/c, especially in $\Delta\phi$ bins not aligned with the reaction plane. Nonetheless the v_2 values for the more peripheral bins reach the same large maximum values, $v_2 \sim 0.2$, at intermediate p_T as the v_2 values for more central bins where the peak in $R_{AA}(p_T)$ is more prominent. Thus, while the peaking in $R_{AA}(p_T)$ is less prominent in the more peripheral bins, the relative difference between the in-plane and out-of-plane π^0 yields in the 40-50% centrality bin is comparable to that in the 20-30% centrality bin. However, it is possible that the large $\Delta\phi$ dependence in the more peripheral bins and the apparent persistence of that variation to high p_T in

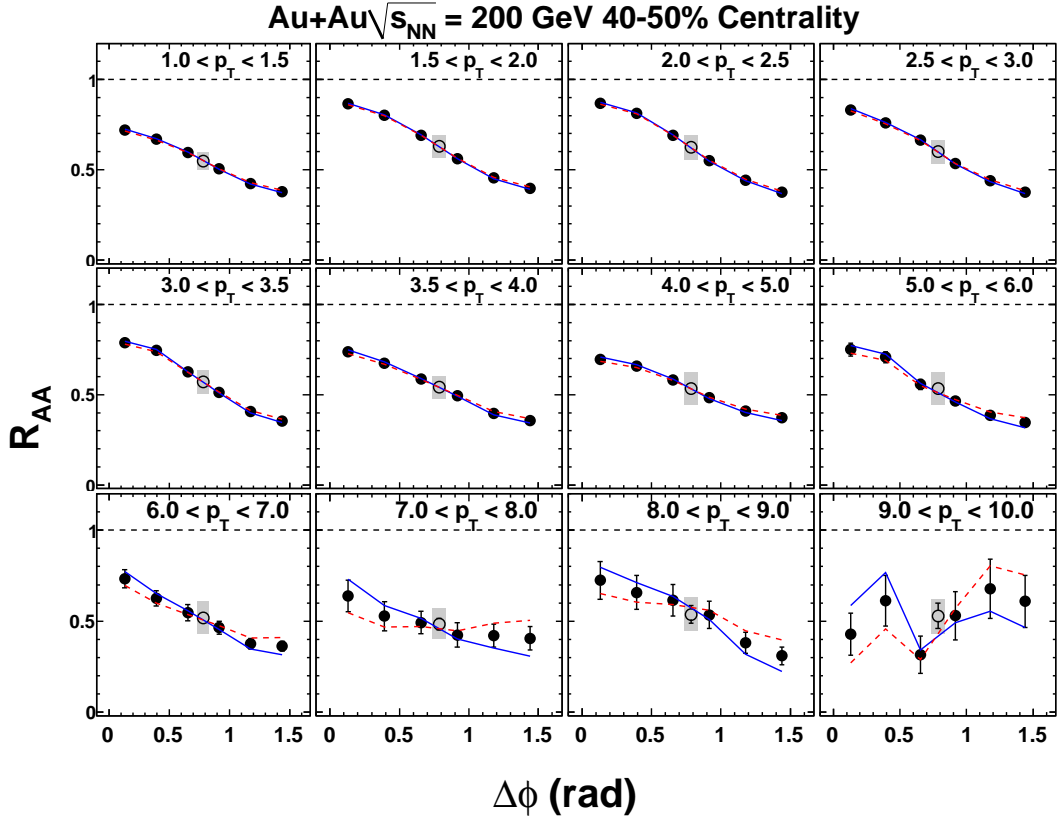


FIG. 13: π^0 R_{AA} versus angle of emission with respect to the reaction plane for 40-50% centrality. Colors/data points as in Fig. 9.

the 40-50% centrality bin more directly reflects the larger spatial anisotropy of the collision zone in more peripheral collisions. The question of whether the π^0 suppression measurements presented here can be understood on the basis of geometry and jet quenching will be more fully explored in the following section.

We have observed above that the p_T and centrality dependence of R_{AA} indicate a correlation between inclusive R_{AA} and v_2 such that the out-of-plane π^0 yields vary only slowly with p_T or centrality while the in-plane yields approach the out-of-plane yields with increasing p_T or increasing N_{part} . Such a correlation between these two seemingly unrelated quantities merely indicates that the yields or R_{AA} of π^0 's measured in-plane and out-of-plane more directly reflect the underlying physics responsible for the azimuthal variation than the $\Delta\phi$ -integrated yield or R_{AA} and the amplitude of the $\Delta\phi$ modulation, v_2 . Indeed, we have argued above that at higher p_T the centrality dependence of $R_{AA}(\Delta\phi)$ may reflect the geometry of jet quenching. At intermediate p_T , the $R_{AA}(p_T)$ results suggest contamination of the in-plane yields by soft production and a simultaneous decrease in R_{AA} and v_2 with increasing p_T as the relative contribution of collective soft processes to π^0 production decreases. To more directly demonstrate the correlation that forms the basis of these arguments we show in Fig. 20 a plot of v_2

versus the inclusive R_{AA} for centralities from 0 to 60%. Data are displayed for $p_T > 2$ GeV/c. The intermediate centrality bins show a correlated increase of v_2 and R_{AA} consistent with the discussion above and a possible saturation of v_2 for larger R_{AA} values. In fact, the trends for different centrality bins appear to be in general agreement. However, their exact relationship and establishing or excluding a causal connection requires further investigation.

C. Nuclear modification factor dependence on path length

The centrality of a collision fixes the geometry of the overlap region between the nuclei, and fixing the angle of emission of the particles further constrains the path length through the medium. We can use this feature to study the dependence of the nuclear modification factor on the path length traversed by the partons. We investigate the path length dependence by expanding on several methods previously described in [25]. We start with three estimators of the path length that are purely geometric, and one that includes the color density of the medium in its calculation:

1. We start by modeling the overlap region as an el-

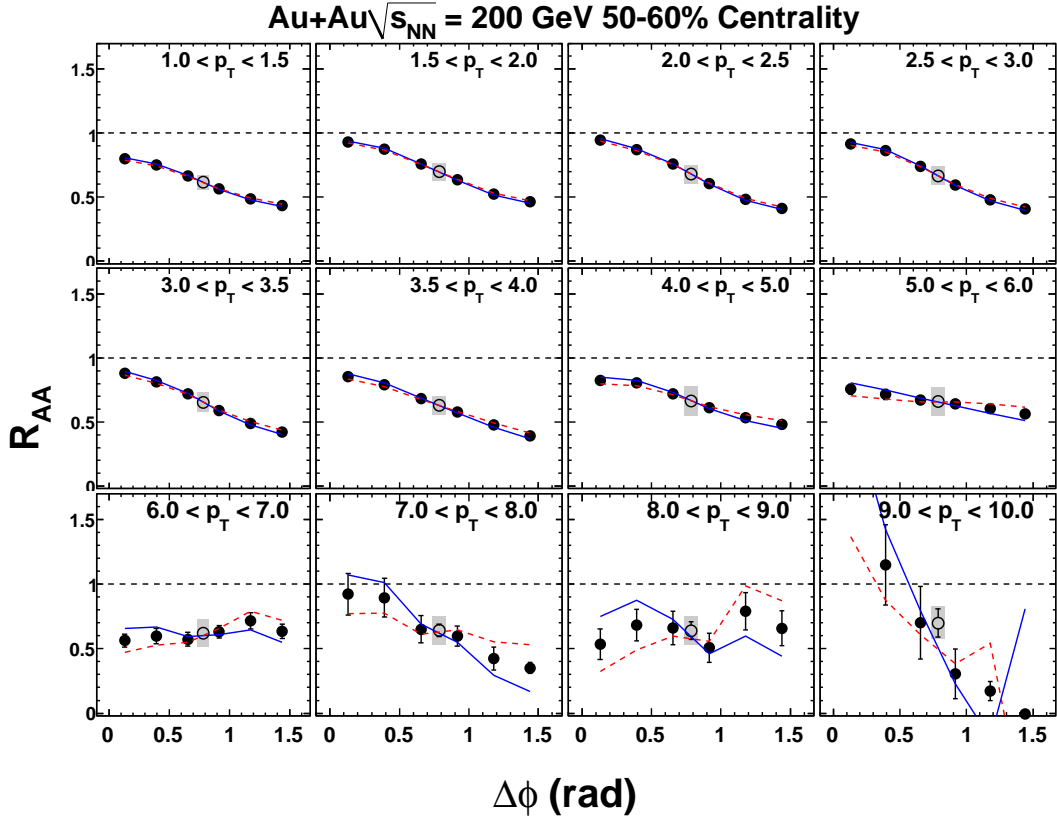


FIG. 14: π^0 R_{AA} versus angle of emission with respect to the reaction plane for 50-60% centrality. Colors/data points as in Fig. 9.

lipse defined by

$$\frac{x^2}{b^2} + \frac{y^2}{a^2} = 1 \quad (14)$$

where the minor axis b is oriented in the x direction and is parallel to the reaction plane. The axes a and b are fixed by the intersection in the transverse plane of two hard spheres with $R = 6.8$ fm. In terms of the spatial eccentricity $\epsilon = \langle y^2 - x^2 \rangle / \langle y^2 + x^2 \rangle$ (often used with Glauber calculations), we can express the distance from the origin to the edge of the ellipse at a given angle:

$$L_\epsilon(\Delta\phi) = \frac{b\sqrt{1+\epsilon}}{\sqrt{1+\epsilon\cos 2\Delta\phi}}. \quad (15)$$

Since this length starts at the origin, and does not take into account color density, the expression provides a very simple estimator with which we can evaluate the dependence of the R_{AA} on path length. We will refer to the hard sphere result as $L_{\epsilon,hs}$.

2. Instead of an ellipse strictly defined by the transverse profile of two hard spheres, we model the collision region as an effective ellipse whose dimensions are determined by equating the RMS radius and

eccentricity to the corresponding quantities calculated from the transverse distribution of participant density based on standard Glauber calculations. This length, L_ϵ , is evaluated using the same expression as Eq. 15, with $b = \sqrt{x^2}$. Both quantities are determined using the PHENIX Glauber model [51].

3. For a more realistic approach, we evaluate the distance along the parton's path weighted by the participant density,

$$\rho L_{xy} = \int_0^\infty dl \rho_{\text{part}}(x_0 + l \cos \Delta\phi, y_0 + l \sin \Delta\phi), \quad (16)$$

where (x_0, y_0) is the hard-scattering position and $\Delta\phi$ is the angle of the jet with respect to the x axis. The jet production point is sampled from a Monte Carlo using a weighted $T_{AA}(x, y)$ distribution and a uniform $\Delta\phi$ distribution. The participant density, assumed to be proportional to the color density, is calculated from the Glauber model. The ρ_{part} density in Eq. 16 is modeled using a 1D Bjorken expansion,

$$\rho_c(\tau) \propto \left(\frac{\tau^2/\tau_0^2}{1 + \tau^2/\tau_0^2} \right) \left(\frac{\tau_0}{\tau} \right).$$

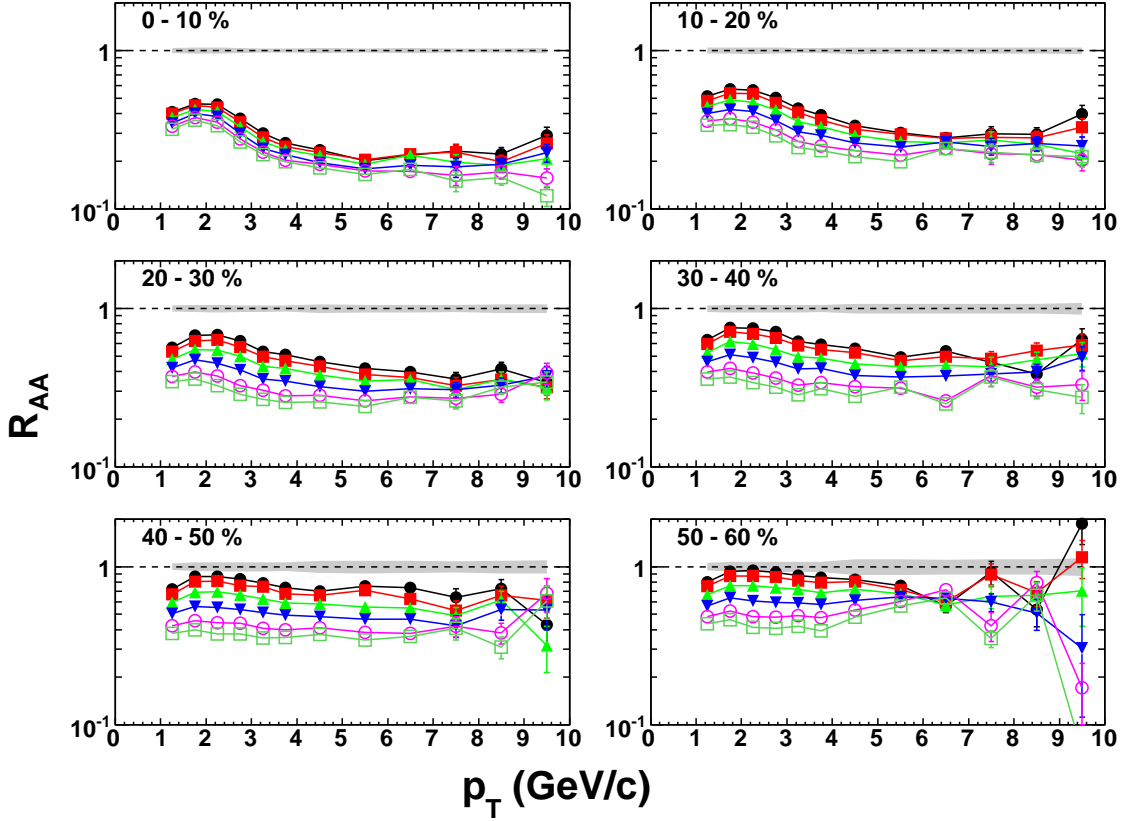


FIG. 15: (Color online) Semi-log plots of $R_{AA}(p_T)$ for each $\Delta\phi$ bin, in different centrality ranges. The $\Delta\phi$ bins are represented as follows: closed (black) circles, 0-15°; closed (red) squares, 15-30°; closed (light green) triangles, 30-45°; closed inverted (blue) triangles, 45-60°; open (magenta) circles, 60-75°; and open (dark green) squares, 75-90°. The systematic error in the inclusive R_{AA} is represented by the grey bands. Errors due to the correction factor have been omitted for clarity.

Thus ρL_{xy} roughly represents LPM energy loss [52]. Note that ρ_c approaches the same $1/\tau$ dependence as the standard $\rho \propto \tau_0/\tau$ but differs from by a factor of 2 at $\tau = \tau_0$ (additionally this form is regular at $\tau = 0$).

4. Finally, we modify ρL_{xy} by normalizing it by the value of the participant density at the center of the collision region, $\rho_{\text{cent}} = \rho_{\text{part}}(0,0)$. As a result, $\rho L_{xy}/\rho_{\text{cent}}$ is an estimator based on geometry alone, but also accounts for the effect of the density distribution both on the jet production point as well as the path from that point to the edge of the medium.

Figs. 21-24 show the R_{AA} dependence on $L_{\epsilon,hs}$, L_{ϵ} , ρL_{xy} , and $\rho L_{xy}/\rho_{\text{cent}}$ respectively. The results shown in this paper cover the p_T range $p_T = 1-10$ GeV/c, not only extending the measurement presented previously but allowing a much finer binning in p_T . The statistical errors in the R_{AA} measurements are represented by error bars (see Section IV B). The systematic errors shown in these data are on the R_{AA} values only, and are indicated by the filled boxes. The major contribution to the system-

atic error in the L_{ϵ} values is the determination of N_{part} , and is at the 10-20% level.

Both the $L_{\epsilon,hs}$ and L_{ϵ} behavior show an interesting degree of scaling. This result is all the more unexpected because of the overly simple geometric picture they represent. Despite the simplistic picture they present, they both exhibit striking universality: the hard sphere $R_{AA}(L_{\epsilon,hs})$ scales well in the low p_T region (as high as $p_T \approx 4$ GeV/c) while $R_{AA}(L_{\epsilon})$ scales well to higher p_T , at least one bin in p_T beyond $L_{\epsilon,hs}$ (though one might argue qualitatively this trend continues even higher when the most peripheral centrality is excluded). The more precise p_T dependence available in this data set reveals a slight deviation from the universality with L_{ϵ} that was previously reported [25].

By contrast, we expect the ρL_{xy} estimator to provide a somewhat more intuitive and concrete picture, as it represents a more realistic approach to the geometry and medium. Since we expect radiative energy loss to play a greater role at high p_T , this should be the estimator that would provide the best scaling. In fact, at the higher p_T range, a universality does emerge, though not until $p_T \approx 6$ GeV/c. Below that value, the measured R_{AA}

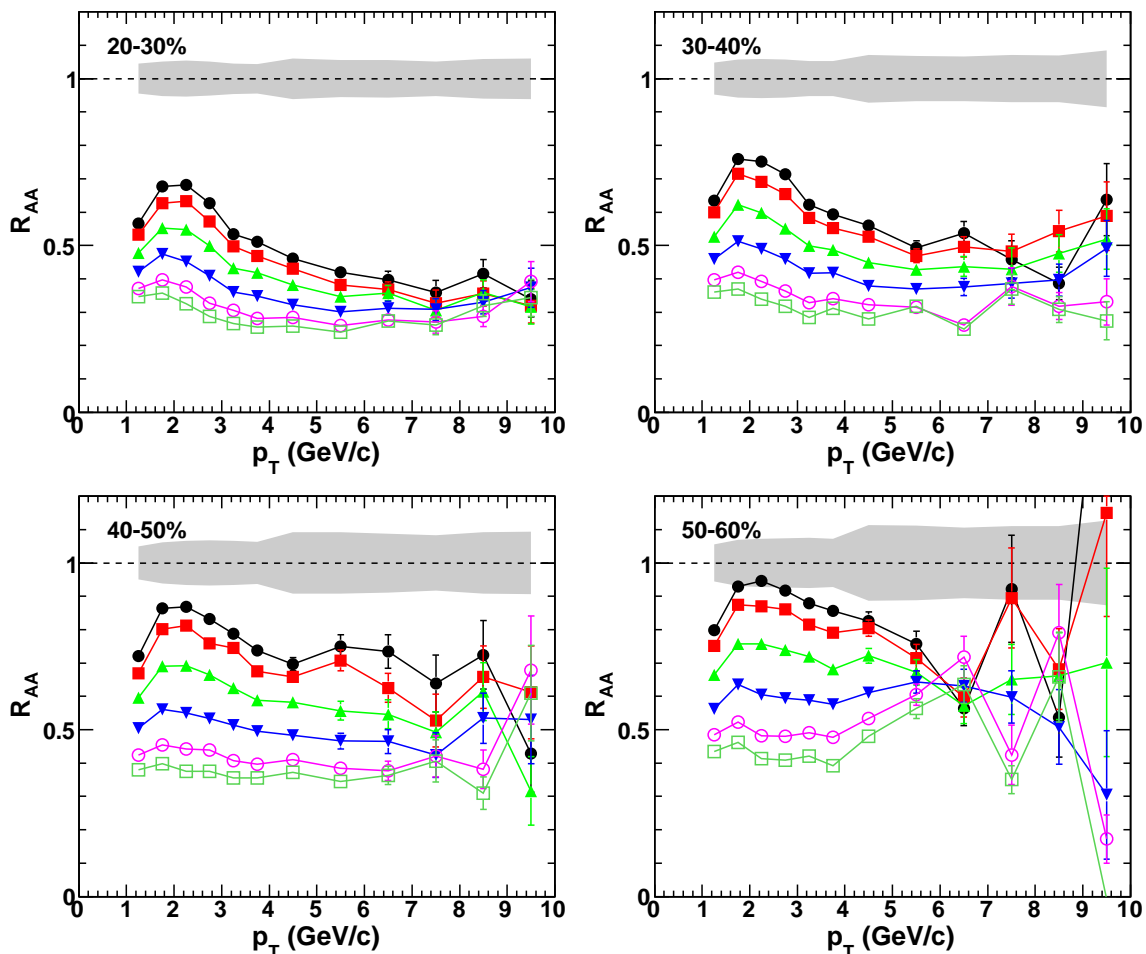


FIG. 16: (Color online) $R_{AA}(p_T)$ for different $\Delta\phi$ bins in the 20-30%, 30-40%, 40-50%, and 50-60% centrality ranges. Colors/data points as in Fig. 15.

points lie on parallel, but separate, curves. When ρL_{xy} is normalized to the central density, data again exhibit a more universal dependence over a wider p_T range than what is seen with ρL_{xy} alone, as shown in Fig. 24.

When considered together these results offer a rich picture. At low to moderate p_T simple geometry may play a larger role in determining the final level of R_{AA} than conventionally thought. At higher p_T the scaling motivated by energy loss (ρL_{xy}) describes the data well. We note that there are three possible (and not necessarily exclusive) interpretations: 1) at low to moderate p_T the combined effects of the boost due to expansion and fragmentation are sensitive primarily to the difference in lengths traveled by the partons, and only weakly dependent on other parameters 2) we need to restrict the analysis of the π^0 R_{AA} to $p_T > 5$ GeV/c to be in the range where fragmentation followed by energy loss dominates, or 3) the assumption that energy loss does not depend linearly on color density [34] is incorrect and leads a departure from scaling with ρL_{xy} at low to moderate p_T .

V. SUMMARY AND CONCLUSIONS

We have presented measurements for the azimuthal anisotropy of neutral pions in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. These measurements include the v_2 and $R_{AA}(\Delta\phi)$ of π^0 s as a function of transverse momentum and centrality. The v_2 has been measured from $p_T \approx 1$ –10 GeV/c in eight centrality bins and four combined centrality bins. The R_{AA} has been measured in the same p_T range in six centrality bins. In addition, the R_{AA} dependence on effective path length through the collision region has been presented for five centralities.

The general trend seen in the $v_2(p_T)$ data is an initial increase in v_2 with increasing p_T , peaking of the v_2 in the region of $2 < p_T < 3$ GeV/c, followed by a decrease in the v_2 . We have argued that such a trend implies a transition from particle production dominated by soft processes to a p_T region dominated by hard processes. In order to quantify the p_T and centrality evolution of v_2 , we have fit its p_T dependence to an empirical expression that allows for such a transition. While the statistical precision of the

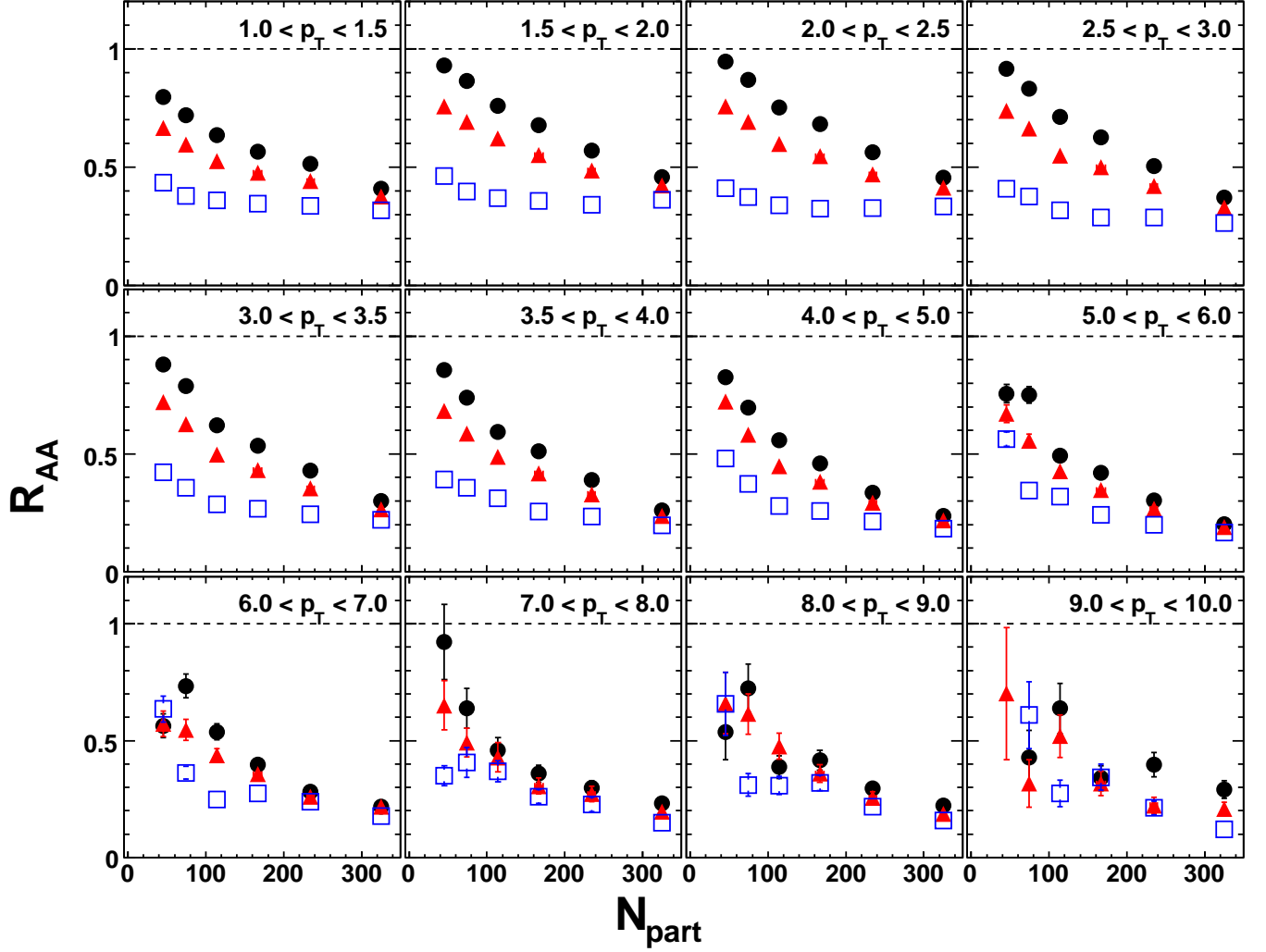


FIG. 17: (Color online) π^0 $R_{AA}(N_{\text{part}})$ in reaction-plane bins at fixed p_T . The three bins are as follows: closed (black) circles are $R_{AA}(0 < \Delta\phi < 15^\circ)$ (in plane), the closed (red) triangles are the $R_{AA}(30 < \Delta\phi < 45^\circ)$, and open (blue) squares are $R_{AA}(85 < \Delta\phi < 90^\circ)$ (out of plane).

high- p_T data limits the conclusions we can draw from the fits, it is clear that the data support the assumption of a decreased dominance of soft processes transitioning to an increased dominance of hard process with increasing p_T . The more peripheral bins suggest that a p_T -independent v_2 may be reached by $p_T \sim 5$ GeV/c.

The differential probes represented by $R_{AA}(\Delta\phi)$ provide a more sophisticated handle on the role of geometry in the collision region. For example, we see that in mid-central collisions the suppression of pions out-of-plane is approximately the same as the suppression in more central collisions. The data suggest that the interplay between the two main effects, namely collective flow and jet quenching, may take place not only along the expected transition in p_T from soft to hard physics, but perhaps also azimuthally, with the quenching effects being dominant along the direction normal to the reaction plane. To further shed light on the transition from soft to hard p_T

regions, we have fit the maxima of mid-central $R_{AA}(p_T)$ in each $\Delta\phi$ range. Between the in and out of plane directions, we observe a shift of 0.4 GeV/c in position of the peak of the spectrum.

In order to further clarify the centrality evolution of the azimuthal dependence of the π^0 suppression, we have presented the R_{AA} as a function of N_{part} in fixed p_T bins, for three directions: along the reaction plane, normal to the reaction plane, and midway between. For $N_{\text{part}} \gtrsim 100$, the R_{AA} along the normal to the reaction plane is almost constant, a trend seen in most p_T bins. By contrast, the R_{AA} nearest to the reaction plane drops by almost a factor of two, converging on the out-of-plane value at the highest N_{part} . This important feature may provide the most compelling argument for geometry as the source of suppression. Since the path length in the direction normal to the reaction plane varies slowly with centrality, we would expect the R_{AA} to be nearly flat. Conversely,

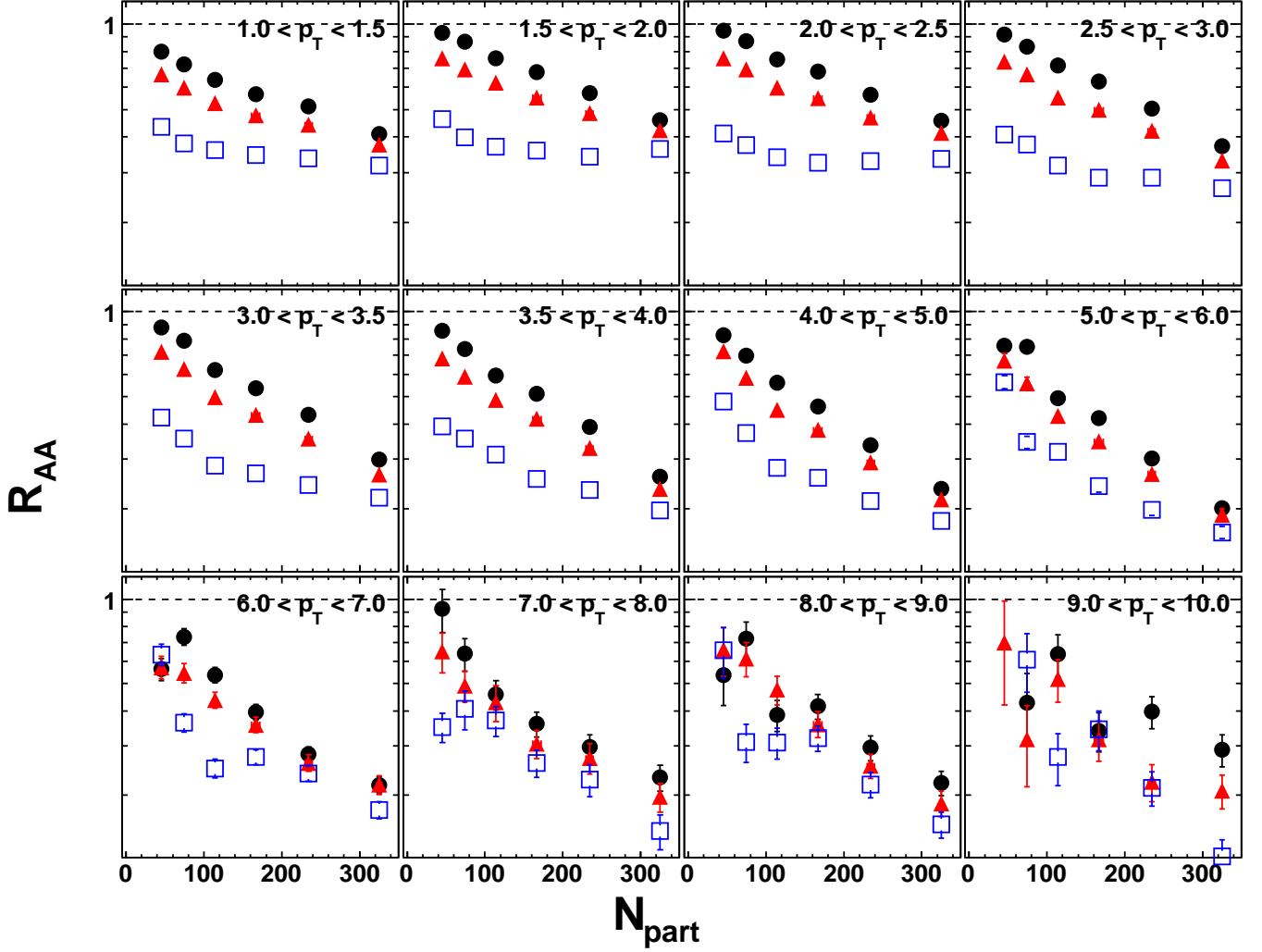


FIG. 18: (Color online) $\pi^0 R_{AA}(N_{\text{part}})$ in reaction-plane bins at fixed p_T , with log scale on the y axis. Colors/data as in Fig. 17.

the in-plane path length will be sensitive to the degree of overlap and strongly influence the observed R_{AA} . Thus it would lead to a small suppression in peripheral collisions while eventually converging on the same value as seen normal to the plane as the anisotropy vanishes in more central collisions. This effect is further borne out in the correlation observed between v_2 and the inclusive R_{AA} . However, we have also argued that contamination from soft production could produce a similar behavior and we have no independent indication of how far in p_T soft contamination might extend. Nonetheless, under both interpretations we can conclude that the R_{AA} for pions produced along the normal to the reaction plane more directly reflects the physics of quenching. We also conclude that the correlation between R_{AA} and v_2 makes separate treatment of these quantities disadvantageous.

We have examined R_{AA} as function of the average path length of the parent parton through the overlap region in the collision, through the estimators $L_{\epsilon,hs}$, L_{ϵ} , $\rho L_{xy}/\rho_{\text{cent}}$, and ρL_{xy} . Each of the first three quantities

represents a progressively more sophisticated estimator for the distance traveled by the parton, with ρL_{xy} at the end providing a proxy for LPM energy loss. Comparison of the scaling with these three measures of lengths seems to suggest that the pion suppression at low- to moderate- p_T is mostly dependent upon simply the geometric length. The estimator that should in principle be the most realistic one, ρL_{xy} , exhibits good universality at the highest p_T values, suggesting that energy loss comparisons should be restricted to the p_T range $p_T > 5$ GeV/c. The importance of simple geometry at low- to moderate- p_T is further supported when ρL_{xy} is normalized by the participant density at the center. This normalization effectively makes ρL_{xy} a length. These geometric descriptions offer a description of the suppression both at low and high p_T regions, clearly showing a transition between the ranges. The features seen in the R_{AA} as function of path length tie in consistently with the observations of a transition in the behavior of the measured v_2 . These two observables, v_2 and $R_{AA}(\Delta\phi)$, analyzed

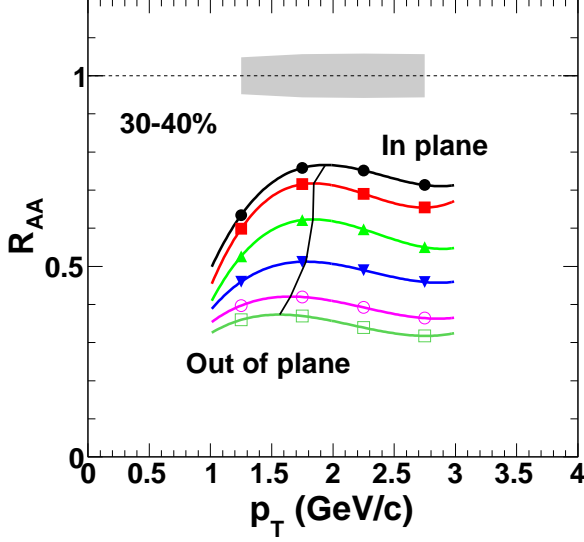


FIG. 19: (Color online) Illustration of the shift in the peak positions in $R_{AA}(p_T)$ for the 30-40% centrality bin. Colors/data points as in Fig. 15.

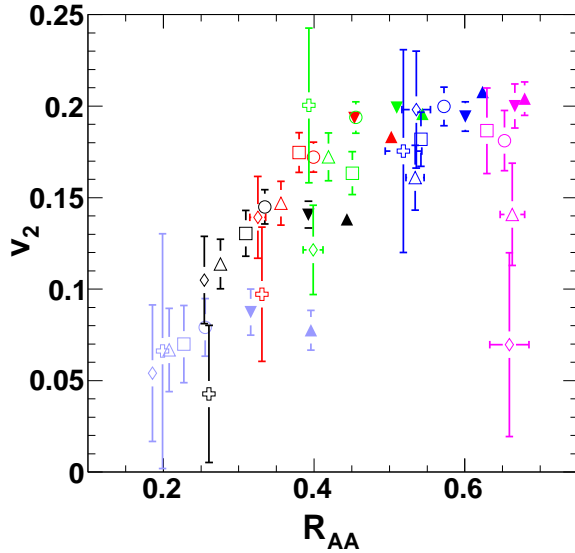


FIG. 20: (Color online) π^0 v_2 vs. inclusive R_{AA} . The points denote bins in p_T as follows: triangles $2 < p_T < 2.5$ GeV/c, inverted triangles $2.5 < p_T < 3$ GeV/c, circles, $3 < p_T < 3.5$ GeV/c; squares, $3.5 < p_T < 4$ GeV/c; open triangles, $4.0 < p_T < 4.5$ GeV/c; diamonds, $4.5 < p_T < 5$ GeV/c; crosses, $5 < p_T < 6$ GeV/c. Centrality bins are indicated by the colors: light blue, 0-10%; black, 10-20%; red, 20-30%; green, 30-40%; blue, 40-50%; magenta 50-60%.

together provide a valuable set of probes for understanding the processes governing the suppression of yields in Au + Au collisions.

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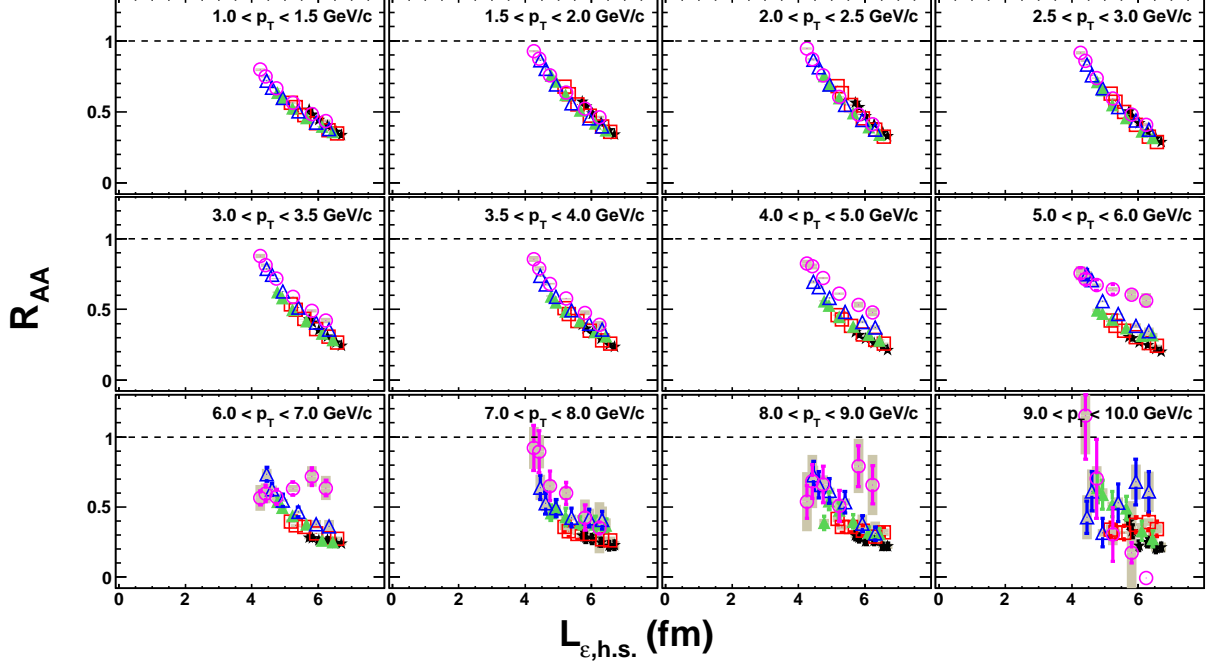


FIG. 21: (Color online) π^0 R_{AA} versus L_{ϵ} based on the hard sphere calculation. Each panel corresponds to a p_T bin. Each data point corresponds to a particular centrality bin and $\Delta\phi$ value. The centralities are represented as follows: (black) stars, 10-20%; open (red) squares, 20-30%; (green) triangles, 30-40%; open (blue) triangles, 40-50%; open (magenta) circles, 50-60%. The height of the boxes represent the systematic errors on R_{AA} for the corresponding L_{ϵ} .

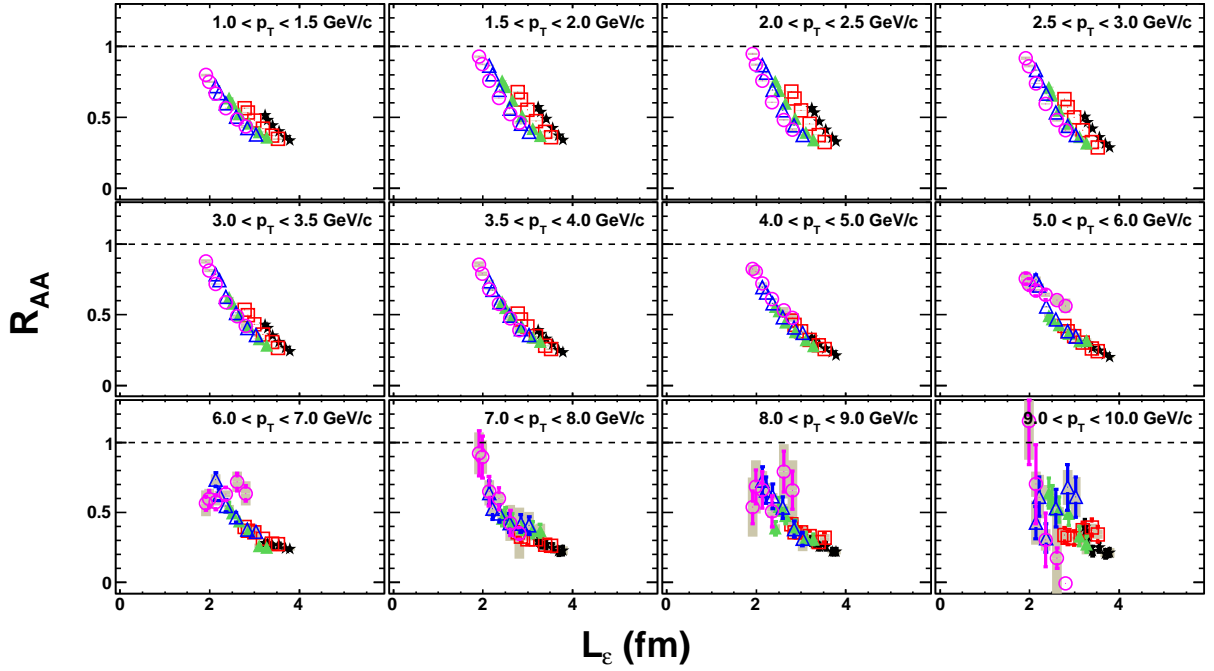


FIG. 22: (Color online) π^0 R_{AA} versus L_{ϵ} based on the RMS radius. Colors/data points as in Fig. 21.

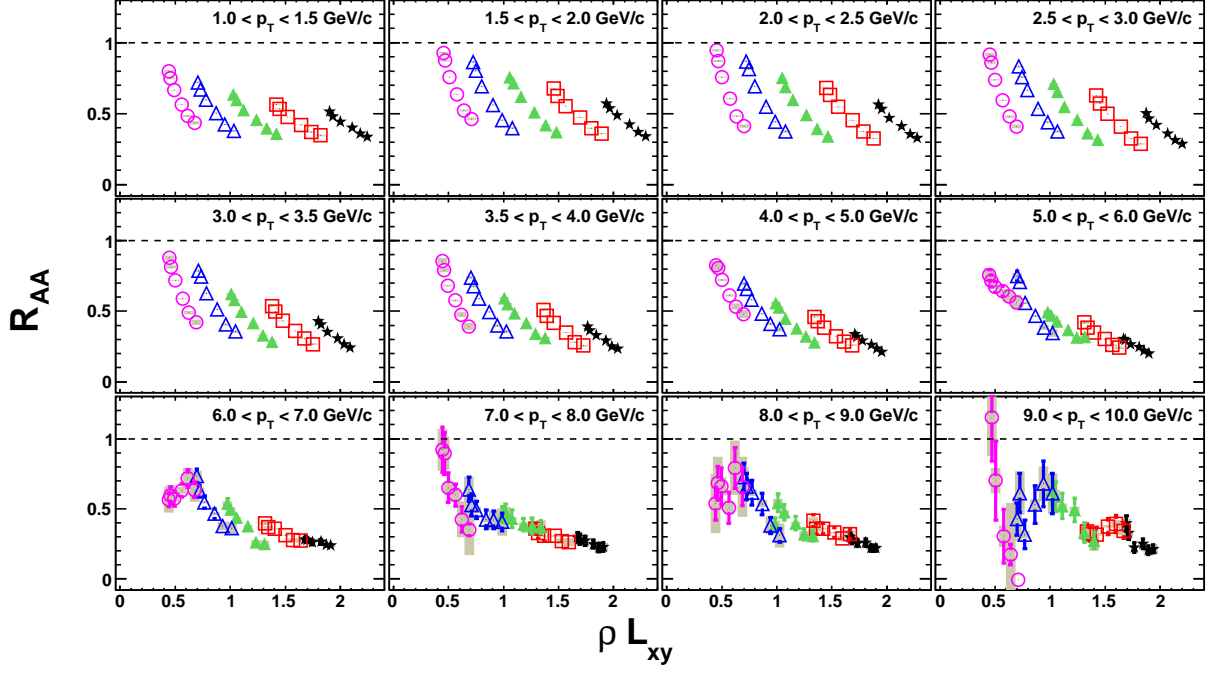


FIG. 23: (Color online) $\pi^0 R_{AA}$ versus ρL_{xy} . The units of ρL_{xy} are participant \times fm. Colors/data points as in Fig. 21.

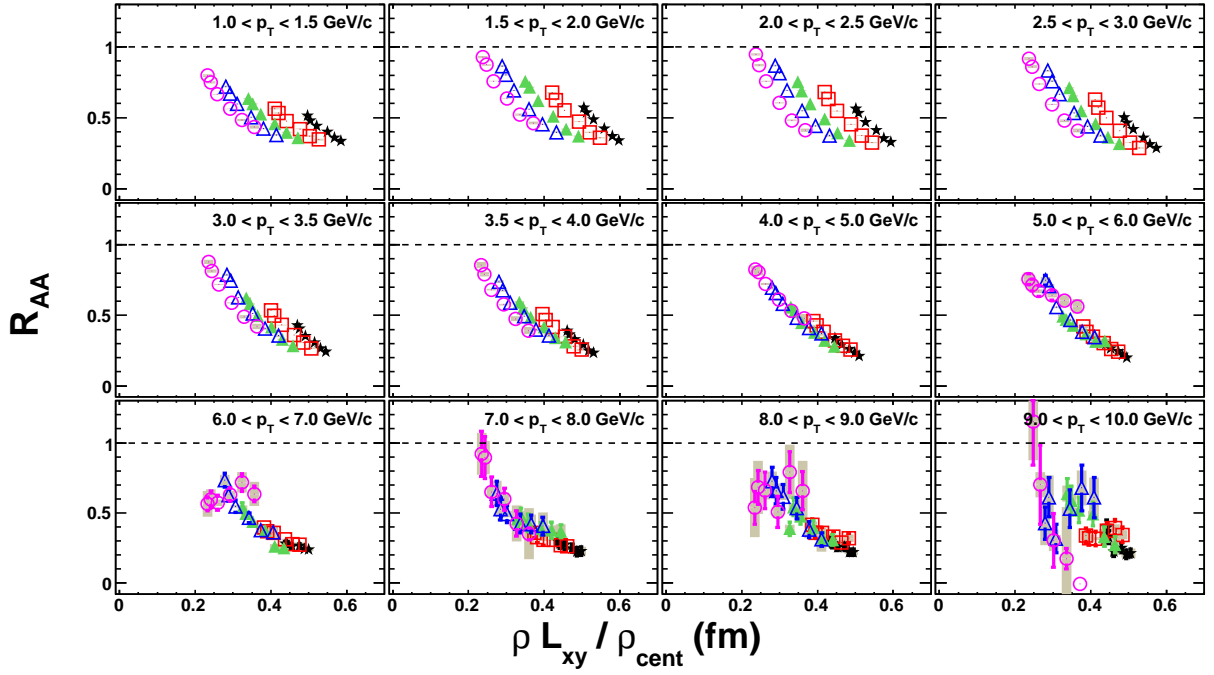


FIG. 24: (Color online) $\pi^0 R_{AA}$ versus $\rho L_{xy}/\rho_{cent}$. The units of $\rho L_{xy}/\rho_{cent}$ are fm. Colors/data points as in Fig. 21.

APPENDIX A: DATA TABLES

TABLE I: π^0 v_2 for 0–5% and 5–10% centrality. All errors are absolute.

Centrality	$\langle p_T \rangle$ GeV/ c	v_2	Stat Err		Syst Err
0–5%	1.21	0.052	+0.034	-0.034	0.011
	1.70	0.035	+0.022	-0.022	0.007
	2.20	0.051	+0.020	-0.020	0.010
	2.70	0.076	+0.023	-0.023	0.016
	3.21	0.039	+0.029	-0.029	0.008
	3.71	0.059	+0.039	-0.039	0.012
	4.37	0.040	+0.042	-0.042	0.008
	5.40	0.040	+0.070	-0.070	0.008
	6.41	0.052	+0.115	-0.115	0.011
	7.43	0.160	+0.206	-0.206	0.033
	8.43	0.168	+0.146	-0.146	0.034
	9.44	0.132	+0.171	-0.171	0.027
5–10%	1.21	0.079	+0.020	-0.020	0.010
	1.71	0.083	+0.013	-0.013	0.010
	2.20	0.106	+0.012	-0.012	0.013
	2.70	0.100	+0.014	-0.014	0.012
	3.21	0.109	+0.018	-0.018	0.014
	3.71	0.075	+0.024	-0.024	0.009
	4.38	0.091	+0.026	-0.026	0.011
	5.40	0.064	+0.041	-0.041	0.008
	6.41	0.062	+0.077	-0.077	0.008
	7.42	0.054	+0.158	-0.158	0.007
	8.43	0.002	+0.097	-0.097	0.0002
	9.44	0.118	+0.136	-0.136	0.015

TABLE II: π^0 v_2 for other centralities. All errors are absolute.

Centrality	$\langle p_T \rangle$ Gev/c	v_2	Stat Err	Syst Err	Centrality	$\langle p_T \rangle$ Gev/c	v_2	Stat Err	Syst Err		
0–10%	1.20	0.066	+0.018	-0.018	0.012	50–60%	1.21	0.153	+0.010	-0.010	0.009
	1.71	0.061	+0.012	-0.012	0.011		1.71	0.175	+0.008	-0.008	0.010
	2.20	0.078	+0.011	-0.011	0.014		2.21	0.204	+0.009	-0.009	0.012
	2.70	0.087	+0.013	-0.013	0.016		2.71	0.200	+0.012	-0.012	0.012
	3.21	0.079	+0.016	-0.016	0.014		3.21	0.181	+0.016	-0.016	0.011
	3.71	0.070	+0.021	-0.021	0.013		3.72	0.187	+0.023	-0.023	0.011
	4.37	0.067	+0.023	-0.023	0.012		4.38	0.141	+0.028	-0.028	0.008
	5.40	0.054	+0.037	-0.037	0.010		5.40	0.070	+0.050	-0.050	0.004
	6.41	0.066	+0.064	-0.064	0.012		6.41	-0.044	+0.097	-0.097	0.003
	7.42	0.112	+0.124	-0.124	0.020		7.42	0.235	+0.168	-0.168	0.014
8.43	0.071	+0.087	-0.087	0.013	8.43	-0.042	+0.234	-0.234	0.002		
9.44	0.189	+0.108	-0.108	0.034	9.44	0.520	+0.428	-0.428	0.031		
10–20%	1.20	0.106	+0.010	-0.010	0.008	0–20%	1.20	0.083	+0.011	-0.011	0.011
	1.71	0.131	+0.006	-0.006	0.010		1.71	0.091	+0.007	-0.007	0.012
	2.20	0.138	+0.006	-0.006	0.010		2.20	0.104	+0.007	-0.007	0.014
	2.70	0.141	+0.007	-0.007	0.010		2.70	0.110	+0.008	-0.008	0.015
	3.21	0.145	+0.009	-0.009	0.011		3.21	0.107	+0.010	-0.010	0.015
	3.71	0.130	+0.012	-0.012	0.010		3.71	0.097	+0.013	-0.013	0.013
	4.37	0.114	+0.014	-0.014	0.008		4.37	0.088	+0.014	-0.014	0.012
	5.40	0.105	+0.024	-0.024	0.008		5.40	0.077	+0.023	-0.023	0.010
	6.41	0.043	+0.037	-0.037	0.003		6.41	0.056	+0.039	-0.039	0.007
	7.42	0.075	+0.088	-0.088	0.006		7.42	0.096	+0.081	-0.079	0.013
8.43	0.076	+0.059	-0.059	0.006	8.43	0.074	+0.055	-0.054	0.010		
9.44	0.151	+0.083	-0.083	0.011	9.44	0.170	+0.074	-0.072	0.023		
20–30%	1.21	0.125	+0.008	-0.008	0.008	20–40%	1.21	0.133	+0.005	-0.005	0.008
	1.71	0.159	+0.005	-0.005	0.010		1.71	0.169	+0.004	-0.004	0.010
	2.20	0.183	+0.005	-0.005	0.011		2.20	0.189	+0.004	-0.004	0.011
	2.70	0.193	+0.006	-0.006	0.012		2.71	0.197	+0.005	-0.005	0.012
	3.21	0.172	+0.008	-0.008	0.010		3.21	0.182	+0.006	-0.006	0.011
	3.71	0.175	+0.011	-0.011	0.010		3.71	0.171	+0.008	-0.008	0.010
	4.38	0.147	+0.012	-0.012	0.009		4.38	0.158	+0.009	-0.009	0.009
	5.40	0.139	+0.022	-0.022	0.008		5.40	0.132	+0.016	-0.016	0.008
	6.41	0.097	+0.037	-0.037	0.006		6.41	0.140	+0.027	-0.027	0.008
	7.42	0.074	+0.073	-0.073	0.004		7.42	0.071	+0.055	-0.054	0.004
8.43	0.070	+0.059	-0.059	0.004	8.43	0.088	+0.045	-0.044	0.005		
9.44	-0.035	+0.087	-0.087	0.002	9.44	0.062	+0.070	-0.069	0.004		
30–40%	1.21	0.143	+0.007	-0.007	0.008	40–60%	1.21	0.159	+0.007	-0.007	0.009
	1.71	0.181	+0.005	-0.005	0.010		1.71	0.188	+0.005	-0.005	0.010
	2.20	0.196	+0.005	-0.005	0.011		2.21	0.208	+0.006	-0.006	0.012
	2.71	0.199	+0.007	-0.007	0.011		2.71	0.198	+0.008	-0.008	0.011
	3.21	0.194	+0.009	-0.009	0.011		3.21	0.195	+0.010	-0.010	0.011
	3.71	0.163	+0.012	-0.012	0.009		3.72	0.185	+0.014	-0.014	0.010
	4.38	0.172	+0.013	-0.013	0.010		4.38	0.155	+0.017	-0.017	0.009
	5.40	0.121	+0.024	-0.024	0.007		5.40	0.149	+0.031	-0.030	0.008
	6.41	0.200	+0.042	-0.042	0.011		6.41	0.093	+0.056	-0.055	0.005
	7.43	0.070	+0.088	-0.088	0.004		7.42	0.152	+0.118	-0.113	0.008
8.43	0.113	+0.071	-0.071	0.006	8.43	0.114	+0.126	-0.124	0.006		
9.44	0.199	+0.118	-0.118	0.011	9.44	0.168	+0.266	-0.231	0.009		
40–50%	1.20	0.160	+0.008	-0.008	0.009	0–92%	1.20	0.106	+0.009	-0.009	0.013
	1.71	0.193	+0.006	-0.006	0.010		1.71	0.125	+0.006	-0.006	0.015
	2.21	0.208	+0.006	-0.006	0.011		2.20	0.142	+0.006	-0.006	0.017
	2.71	0.194	+0.008	-0.008	0.010		2.71	0.146	+0.008	-0.008	0.018
	3.21	0.200	+0.011	-0.011	0.011		3.21	0.143	+0.011	-0.011	0.017
	3.72	0.182	+0.015	-0.015	0.010		3.71	0.136	+0.015	-0.015	0.016
	4.38	0.161	+0.018	-0.018	0.009		4.38	0.127	+0.017	-0.017	0.015
	5.40	0.198	+0.032	-0.032	0.011		5.40	0.108	+0.033	-0.033	0.013
	6.41	0.175	+0.055	-0.055	0.009		6.41	0.084	+0.059	-0.059	0.010
	7.42	0.106	+0.133	-0.133	0.006		7.42	0.083	+0.136	-0.145	0.009
8.43	0.196	+0.112	-0.112	0.011	8.43	0.113	+0.099	-0.109	0.011		
9.44	-0.084	+0.214	-0.214	0.005	9.44	0.149	+0.156	-0.123	0.012		

TABLE III: R_{AA} vs. path length for (upper) $1.0 < p_T < 1.5$ and (lower) $1.5 < p_T < 2.0$ GeV/c.

Centrality	$\Delta\phi$	L_ϵ	ρL_{xy}	R_{AA}	Stat Error(abs)	Sys Error(abs)
10-20%	0-15	3.23	1.90	0.514	0.009	0.005
	15-30	3.29	1.93	0.481	0.009	0.003
	30-45	3.41	2.00	0.443	0.008	0.001
	45-60	3.55	2.11	0.400	0.007	0.001
	60-75	3.69	2.18	0.358	0.007	0.004
	75-90	3.78	2.24	0.337	0.006	0.006
20-30%	0-15	2.78	1.42	0.565	0.009	0.004
	15-30	2.85	1.45	0.533	0.008	0.003
	30-45	2.99	1.52	0.477	0.008	0.001
	45-60	3.19	1.64	0.421	0.007	0.001
	60-75	3.39	1.74	0.371	0.006	0.003
	75-90	3.52	1.82	0.346	0.006	0.005
30-40%	0-15	2.43	1.03	0.634	0.009	0.004
	15-30	2.50	1.06	0.599	0.009	0.003
	30-45	2.66	1.12	0.526	0.008	0.001
	45-60	2.87	1.24	0.459	0.007	0.001
	60-75	3.11	1.33	0.397	0.006	0.004
	75-90	3.27	1.42	0.360	0.005	0.005
40-50%	0-15	2.14	0.70	0.721	0.009	0.005
	15-30	2.21	0.73	0.669	0.009	0.004
	30-45	2.37	0.78	0.596	0.008	0.002
	45-60	2.59	0.87	0.505	0.007	0.002
	60-75	2.84	0.95	0.424	0.006	0.005
	75-90	3.03	1.03	0.379	0.005	0.007
50-60%	0-15	1.92	0.44	0.798	0.010	0.009
	15-30	1.99	0.46	0.751	0.010	0.007
	30-45	2.14	0.49	0.665	0.008	0.002
	45-60	2.36	0.56	0.562	0.007	0.003
	60-75	2.61	0.61	0.485	0.006	0.007
	75-90	2.81	0.68	0.435	0.006	0.010
Centrality	$\Delta\phi$	L_ϵ	ρL_{xy}	R_{AA}	Stat Error(abs)	Sys Error(abs)
10-20%	0-15	3.23	1.94	0.570	0.007	0.003
	15-30	3.29	1.96	0.539	0.007	0.002
	30-45	3.41	2.03	0.486	0.006	0.001
	45-60	3.55	2.15	0.424	0.009	0.001
	60-75	3.69	2.22	0.370	0.005	0.003
	75-90	3.78	2.29	0.341	0.005	0.004
20-30%	0-15	2.78	1.46	0.677	0.008	0.003
	15-30	2.85	1.49	0.626	0.008	0.002
	30-45	2.99	1.57	0.552	0.007	0.001
	45-60	3.19	1.70	0.475	0.006	0.001
	60-75	3.39	1.80	0.397	0.005	0.002
	75-90	3.52	1.89	0.358	0.004	0.003
30-40%	0-15	2.43	1.06	0.758	0.009	0.003
	15-30	2.50	1.09	0.716	0.008	0.002
	30-45	2.66	1.16	0.622	0.007	0.001
	45-60	2.87	1.28	0.512	0.006	0.001
	60-75	3.11	1.38	0.420	0.005	0.003
	75-90	3.27	1.48	0.370	0.004	0.004
40-50%	0-15	2.14	0.72	0.865	0.010	0.004
	15-30	2.21	0.75	0.802	0.009	0.003
	30-45	2.37	0.80	0.691	0.008	0.001
	45-60	2.59	0.90	0.561	0.006	0.001
	60-75	2.84	0.99	0.455	0.005	0.004
	75-90	3.03	1.08	0.398	0.005	0.006
50-60%	0-15	1.92	0.45	0.929	0.010	0.008
	15-30	1.99	0.47	0.874	0.010	0.006
	30-45	2.14	0.51	0.757	0.009	0.002
	45-60	2.36	0.58	0.635	0.007	0.002
	60-75	2.61	0.64	0.523	0.006	0.007
	75-90	2.81	0.71	0.462	0.005	0.009

TABLE IV: R_{AA} vs. path length for (upper) $2.0 < p_T < 2.5$ and (lower) $2.5 < p_T < 3.0$ GeV/c.

Centrality	$\Delta\phi$	L_ϵ	ρL_{xy}	R_{AA}	Stat Error(abs)	Sys Error(abs)
10-20%	0-15	3.23	1.92	0.562	0.007	0.003
	15-30	3.29	1.95	0.534	0.007	0.002
	30-45	3.41	2.02	0.470	0.006	0.001
	45-60	3.55	2.13	0.413	0.006	0.001
	60-75	3.69	2.21	0.354	0.005	0.003
	75-90	3.78	2.28	0.329	0.004	0.004
20-30%	0-15	2.78	1.45	0.681	0.008	0.003
	15-30	2.85	1.48	0.633	0.008	0.002
	30-45	2.99	1.56	0.547	0.007	0.001
	45-60	3.19	1.69	0.452	0.006	0.001
	60-75	3.39	1.79	0.375	0.005	0.003
	75-90	3.52	1.88	0.325	0.004	0.004
30-40%	0-15	2.43	1.05	0.752	0.009	0.003
	15-30	2.50	1.08	0.691	0.008	0.002
	30-45	2.66	1.15	0.597	0.007	0.001
	45-60	2.87	1.27	0.490	0.006	0.001
	60-75	3.11	1.37	0.392	0.005	0.003
	75-90	3.27	1.46	0.339	0.004	0.004
40-50%	0-15	2.14	0.72	0.869	0.010	0.005
	15-30	2.21	0.75	0.813	0.009	0.004
	30-45	2.37	0.80	0.691	0.008	0.001
	45-60	2.59	0.90	0.550	0.006	0.001
	60-75	2.84	0.99	0.443	0.005	0.004
	75-90	3.03	1.08	0.375	0.004	0.006
50-60%	0-15	1.92	0.45	0.946	0.011	0.009
	15-30	1.99	0.47	0.870	0.010	0.007
	30-45	2.14	0.50	0.757	0.009	0.003
	45-60	2.36	0.57	0.606	0.007	0.003
	60-75	2.61	0.63	0.482	0.006	0.007
	75-90	2.81	0.70	0.413	0.005	0.010
Centrality	$\Delta\phi$	L_ϵ	ρL_{xy}	R_{AA}	Stat Error(abs)	Sys Error(abs)
10-20%	0-15	3.23	1.87	0.504	0.007	0.003
	15-30	3.29	1.90	0.467	0.007	0.002
	30-45	3.41	1.96	0.421	0.006	0.001
	45-60	3.55	2.07	0.360	0.005	0.001
	60-75	3.69	2.14	0.315	0.005	0.003
	75-90	3.78	2.20	0.288	0.004	0.004
20-30%	0-15	2.78	1.42	0.626	0.009	0.003
	15-30	2.85	1.45	0.573	0.008	0.002
	30-45	2.99	1.52	0.499	0.007	0.001
	45-60	3.19	1.64	0.409	0.006	0.001
	60-75	3.39	1.74	0.326	0.005	0.003
	75-90	3.52	1.82	0.287	0.004	0.004
30-40%	0-15	2.43	1.03	0.713	0.009	0.004
	15-30	2.50	1.07	0.654	0.009	0.003
	30-45	2.66	1.13	0.550	0.007	0.001
	45-60	2.87	1.25	0.459	0.006	0.001
	60-75	3.11	1.34	0.364	0.005	0.003
	75-90	3.27	1.43	0.318	0.004	0.005
40-50%	0-15	2.14	0.72	0.832	0.011	0.006
	15-30	2.21	0.74	0.758	0.010	0.004
	30-45	2.37	0.79	0.665	0.009	0.002
	45-60	2.59	0.89	0.534	0.007	0.002
	60-75	2.84	0.98	0.439	0.006	0.005
	75-90	3.03	1.07	0.376	0.005	0.007
50-60%	0-15	1.92	0.45	0.916	0.012	0.011
	15-30	1.99	0.47	0.861	0.011	0.008
	30-45	2.14	0.50	0.738	0.010	0.003
	45-60	2.36	0.57	0.594	0.008	0.003
	60-75	2.61	0.63	0.480	0.006	0.010
	75-90	2.81	0.70	0.409	0.006	0.013

TABLE V: R_{AA} vs. path length for (upper) $3.0 < p_T < 3.5$ and (lower) $3.5 < p_T < 4.0$ GeV/c.

Centrality	$\Delta\phi$	L_ϵ	ρL_{xy}	R_{AA}	Stat Error(abs)	Sys Error(abs)
10–20%	0–15	3.23	1.80	0.430	0.008	0.003
	15–30	3.29	1.82	0.405	0.007	0.003
	30–45	3.41	1.88	0.355	0.006	0.001
	45–60	3.55	1.97	0.307	0.006	0.001
	60–75	3.69	2.04	0.266	0.005	0.003
	75–90	3.78	2.09	0.243	0.004	0.004
20–30%	0–15	2.78	1.38	0.534	0.009	0.003
	15–30	2.85	1.41	0.497	0.008	0.003
	30–45	2.99	1.48	0.431	0.007	0.001
	45–60	3.19	1.59	0.360	0.006	0.001
	60–75	3.39	1.67	0.305	0.005	0.003
	75–90	3.52	1.75	0.267	0.005	0.004
30–40%	0–15	2.43	1.01	0.622	0.010	0.004
	15–30	2.50	1.04	0.582	0.009	0.003
	30–45	2.66	1.10	0.498	0.008	0.001
	45–60	2.87	1.21	0.417	0.007	0.001
	60–75	3.11	1.30	0.328	0.005	0.004
	75–90	3.27	1.38	0.285	0.005	0.006
40–50%	0–15	2.14	0.71	0.788	0.012	0.007
	15–30	2.21	0.74	0.745	0.012	0.006
	30–45	2.37	0.79	0.625	0.010	0.002
	45–60	2.59	0.88	0.514	0.008	0.002
	60–75	2.84	0.96	0.407	0.007	0.007
	75–90	3.03	1.05	0.355	0.006	0.009
50–60%	0–15	1.92	0.45	0.880	0.015	0.015
	15–30	1.99	0.46	0.814	0.014	0.011
	30–45	2.14	0.50	0.720	0.012	0.004
	45–60	2.36	0.57	0.589	0.010	0.004
	60–75	2.61	0.63	0.490	0.008	0.013
	75–90	2.81	0.69	0.421	0.007	0.018
Centrality	$\Delta\phi$	L_ϵ	ρL_{xy}	R_{AA}	Stat Error(abs)	Sys Error(abs)
10–20%	0–15	3.23	1.76	0.390	0.009	0.004
	15–30	3.29	1.78	0.364	0.008	0.003
	30–45	3.41	1.84	0.329	0.007	0.001
	45–60	3.55	1.93	0.291	0.007	0.001
	60–75	3.69	1.99	0.249	0.006	0.004
	75–90	3.78	2.04	0.234	0.005	0.005
20–30%	0–15	2.78	1.36	0.511	0.011	0.004
	15–30	2.85	1.39	0.468	0.010	0.003
	30–45	2.99	1.46	0.418	0.009	0.001
	45–60	3.19	1.57	0.348	0.007	0.001
	60–75	3.39	1.65	0.281	0.006	0.004
	75–90	3.52	1.72	0.256	0.005	0.006
30–40%	0–15	2.43	1.01	0.593	0.012	0.006
	15–30	2.50	1.04	0.552	0.011	0.004
	30–45	2.66	1.10	0.487	0.010	0.002
	45–60	2.87	1.21	0.418	0.008	0.002
	60–75	3.11	1.29	0.341	0.007	0.005
	75–90	3.27	1.38	0.311	0.007	0.007
40–50%	0–15	2.14	0.70	0.738	0.015	0.010
	15–30	2.21	0.73	0.676	0.014	0.007
	30–45	2.37	0.78	0.588	0.012	0.003
	45–60	2.59	0.87	0.495	0.010	0.003
	60–75	2.84	0.95	0.397	0.008	0.009
	75–90	3.03	1.03	0.356	0.008	0.012
50–60%	0–15	1.92	0.44	0.856	0.019	0.021
	15–30	1.99	0.46	0.791	0.017	0.015
	30–45	2.14	0.50	0.682	0.015	0.006
	45–60	2.36	0.56	0.577	0.013	0.006
	60–75	2.61	0.62	0.477	0.011	0.018
	75–90	2.81	0.68	0.392	0.009	0.023

TABLE VI: R_{AA} vs. path length for (upper) $4.0 < p_T < 5.0$ and (lower) $5.0 < p_T < 6.0$ GeV/c.

Centrality	$\Delta\phi$	L_ϵ	ρL_{xy}	R_{AA}	Stat Error(abs)	Sys Error(abs)
10-20%	0-15	3.23	1.71	0.336	0.010	0.004
	15-30	3.29	1.73	0.319	0.009	0.003
	30-45	3.41	1.78	0.292	0.009	0.001
	45-60	3.55	1.86	0.261	0.008	0.001
	60-75	3.69	1.91	0.234	0.007	0.004
	75-90	3.78	1.95	0.213	0.006	0.005
20-30%	0-15	2.78	1.34	0.461	0.012	0.004
	15-30	2.85	1.37	0.430	0.012	0.003
	30-45	2.99	1.43	0.381	0.010	0.001
	45-60	3.19	1.54	0.322	0.009	0.001
	60-75	3.39	1.61	0.284	0.008	0.004
	75-90	3.52	1.68	0.258	0.007	0.006
30-40%	0-15	2.43	0.99	0.559	0.015	0.006
	15-30	2.50	1.02	0.527	0.014	0.005
	30-45	2.66	1.08	0.448	0.012	0.002
	45-60	2.87	1.18	0.379	0.010	0.002
	60-75	3.11	1.26	0.322	0.009	0.006
	75-90	3.27	1.34	0.279	0.008	0.008
40-50%	0-15	2.14	0.70	0.697	0.020	0.012
	15-30	2.21	0.72	0.658	0.019	0.009
	30-45	2.37	0.77	0.583	0.016	0.003
	45-60	2.59	0.87	0.483	0.014	0.004
	60-75	2.84	0.94	0.411	0.012	0.010
	75-90	3.03	1.02	0.372	0.011	0.014
50-60%	0-15	1.92	0.45	0.826	0.026	0.026
	15-30	1.99	0.47	0.804	0.025	0.020
	30-45	2.14	0.50	0.722	0.022	0.008
	45-60	2.36	0.57	0.611	0.019	0.008
	60-75	2.61	0.63	0.534	0.017	0.022
	75-90	2.81	0.70	0.480	0.0155	0.030
Centrality	$\Delta\phi$	L_ϵ	ρL_{xy}	R_{AA}	Stat Error(abs)	Sys Error(abs)
10-20%	0-15	3.23	1.67	0.301	0.014	0.007
	15-30	3.29	1.68	0.294	0.013	0.005
	30-45	3.41	1.73	0.267	0.012	0.002
	45-60	3.55	1.81	0.246	0.011	0.002
	60-75	3.69	1.85	0.218	0.010	0.006
	75-90	3.78	1.90	0.199	0.009	0.008
20-30%	0-15	2.78	1.31	0.420	0.018	0.008
	15-30	2.85	1.34	0.382	0.017	0.006
	30-45	2.99	1.40	0.347	0.015	0.002
	45-60	3.19	1.50	0.301	0.013	0.002
	60-75	3.39	1.56	0.260	0.012	0.007
	75-90	3.52	1.63	0.240	0.011	0.010
30-40%	0-15	2.43	0.98	0.492	0.022	0.011
	15-30	2.50	1.01	0.469	0.020	0.008
	30-45	2.66	1.06	0.428	0.019	0.003
	45-60	2.87	1.17	0.370	0.017	0.003
	60-75	3.11	1.24	0.315	0.015	0.009
	75-90	3.27	1.32	0.318	0.014	0.014
40-50%	0-15	2.14	0.70	0.750	0.035	0.021
	15-30	2.21	0.72	0.708	0.032	0.016
	30-45	2.37	0.77	0.557	0.028	0.006
	45-60	2.59	0.87	0.466	0.023	0.006
	60-75	2.84	0.94	0.385	0.019	0.019
	75-90	3.03	1.02	0.345	0.017	0.027
50-60%	0-15	1.92	0.45	0.757	0.039	0.050
	15-30	1.99	0.47	0.715	0.040	0.036
	30-45	2.14	0.50	0.672	0.038	0.013
	45-60	2.36	0.57	0.642	0.033	0.014
	60-75	2.61	0.63	0.605	0.032	0.038
	75-90	2.81	0.69	0.563	0.030	0.051

TABLE VII: R_{AA} vs. path length for (upper) $6.0 < p_T < 7.0$ and (lower) $7.0 < p_T < 8.0$ GeV/ c .

Centrality	$\Delta\phi$	L_ϵ	ρL_{xy}	R_{AA}	Stat Error(abs)	Sys Error(abs)
10–20%	0–15	3.23	1.68	0.281	0.017	0.011
	15–30	3.29	1.70	0.278	0.017	0.008
	30–45	3.41	1.75	0.261	0.017	0.003
	45–60	3.55	1.82	0.264	0.018	0.003
	60–75	3.69	1.87	0.241	0.015	0.009
	75–90	3.78	1.91	0.240	0.015	0.012
20–30%	0–15	2.78	1.32	0.396	0.026	0.013
	15–30	2.85	1.34	0.368	0.023	0.010
	30–45	2.99	1.40	0.357	0.023	0.004
	45–60	3.19	1.50	0.312	0.021	0.004
	60–75	3.39	1.57	0.277	0.018	0.011
	75–90	3.52	1.64	0.274	0.017	0.016
30–40%	0–15	2.43	0.98	0.537	0.035	0.018
	15–30	2.50	1.00	0.496	0.030	0.013
	30–45	2.66	1.06	0.437	0.029	0.005
	45–60	2.87	1.16	0.376	0.026	0.006
	60–75	3.11	1.23	0.261	0.018	0.015
	75–90	3.27	1.31	0.249	0.019	0.025
40–50%	0–15	2.14	0.70	0.734	0.050	0.038
	15–30	2.21	0.72	0.625	0.043	0.026
	30–45	2.37	0.77	0.546	0.044	0.010
	45–60	2.59	0.86	0.465	0.036	0.011
	60–75	2.84	0.93	0.377	0.029	0.030
	75–90	3.03	1.01	0.363	0.027	0.046
50–60%	0–15	1.92	0.44	0.564	0.051	0.093
	15–30	1.99	0.46	0.597	0.059	0.070
	30–45	2.14	0.49	0.572	0.054	0.023
	45–60	2.36	0.56	0.631	0.049	0.024
	60–75	2.61	0.62	0.717	0.063	0.072
	75–90	2.81	0.68	0.635	0.056	0.085
Centrality	$\Delta\phi$	L_ϵ	ρL_{xy}	R_{AA}	Stat Error(abs)	Sys Error(abs)
10–20%	0–15	3.23	1.67	0.297	0.032	0.026
	15–30	3.29	1.69	0.282	0.037	0.019
	30–45	3.41	1.74	0.272	0.034	0.007
	45–60	3.55	1.82	0.248	0.030	0.007
	60–75	3.69	1.86	0.222	0.031	0.020
	75–90	3.78	1.91	0.227	0.030	0.030
20–30%	0–15	2.78	1.29	0.359	0.037	0.025
	15–30	2.85	1.31	0.327	0.040	0.018
	30–45	2.99	1.37	0.306	0.035	0.007
	45–60	3.19	1.47	0.308	0.033	0.007
	60–75	3.39	1.53	0.270	0.033	0.020
	75–90	3.52	1.59	0.261	0.029	0.027
30–40%	0–15	2.43	0.99	0.458	0.055	0.042
	15–30	2.50	1.02	0.482	0.052	0.033
	30–45	2.66	1.08	0.429	0.063	0.012
	45–60	2.87	1.18	0.387	0.044	0.012
	60–75	3.11	1.26	0.377	0.057	0.034
	75–90	3.27	1.34	0.369	0.045	0.048
40–50%	0–15	2.14	0.69	0.639	0.086	0.091
	15–30	2.21	0.71	0.527	0.079	0.058
	30–45	2.37	0.75	0.492	0.062	0.022
	45–60	2.59	0.84	0.424	0.066	0.022
	60–75	2.84	0.91	0.420	0.062	0.069
	75–90	3.03	0.99	0.406	0.063	0.099
50–60%	0–15	1.92	0.45	0.922	0.161	0.149
	15–30	1.99	0.46	0.895	0.150	0.118
	30–45	2.14	0.50	0.651	0.106	0.039
	45–60	2.36	0.56	0.598	0.078	0.048
	60–75	2.61	0.62	0.424	0.089	0.128
	75–90	2.81	0.69	0.351	0.042	0.182

TABLE VIII: R_{AA} vs. path length for (upper) $8.0 < p_T < 9.0$ and (lower) $9.0 < p_T < 10.0$ GeV/c.

Centrality	$\Delta\phi$	L_ϵ	ρL_{xy}	R_{AA}	Stat Error(abs)	Sys Error(abs)
10-20%	0-15	3.23	1.67	0.296	0.030	0.017
	15-30	3.29	1.68	0.280	0.029	0.013
	30-45	3.41	1.73	0.255	0.026	0.005
	45-60	3.55	1.81	0.258	0.026	0.005
	60-75	3.69	1.86	0.220	0.023	0.013
	75-90	3.78	1.90	0.219	0.022	0.019
20-30%	0-15	2.78	1.33	0.415	0.043	0.024
	15-30	2.85	1.36	0.356	0.038	0.016
	30-45	2.99	1.42	0.359	0.038	0.006
	45-60	3.19	1.52	0.329	0.035	0.006
	60-75	3.39	1.59	0.288	0.032	0.017
	75-90	3.52	1.66	0.320	0.033	0.027
30-40%	0-15	2.43	0.98	0.387	0.049	0.026
	15-30	2.50	1.01	0.543	0.063	0.029
	30-45	2.66	1.07	0.476	0.056	0.010
	45-60	2.87	1.17	0.396	0.048	0.010
	60-75	3.11	1.25	0.318	0.041	0.026
	75-90	3.27	1.32	0.308	0.039	0.037
40-50%	0-15	2.14	0.70	0.724	0.103	0.072
	15-30	2.21	0.73	0.658	0.094	0.053
	30-45	2.37	0.77	0.614	0.087	0.022
	45-60	2.59	0.87	0.535	0.076	0.025
	60-75	2.84	0.94	0.382	0.058	0.065
	75-90	3.03	1.03	0.310	0.048	0.086
50-60%	0-15	1.92	0.45	0.536	0.118	0.212
	15-30	1.99	0.46	0.682	0.121	0.192
	30-45	2.14	0.50	0.661	0.130	0.065
	45-60	2.36	0.56	0.508	0.112	0.047
	60-75	2.61	0.62	0.791	0.144	0.193
	75-90	2.81	0.69	0.658	0.135	0.215
Centrality	$\Delta\phi$	L_ϵ	ρL_{xy}	R_{AA}	Stat Error(abs)	Sys Error(abs)
10-20%	0-15	3.23	1.69	0.397	0.051	0.028
	15-30	3.29	1.71	0.327	0.045	0.018
	30-45	3.41	1.76	0.223	0.034	0.005
	45-60	3.55	1.84	0.249	0.035	0.007
	60-75	3.69	1.89	0.203	0.030	0.021
	75-90	3.78	1.94	0.213	0.030	0.034
20-30%	0-15	2.78	1.33	0.340	0.054	0.038
	15-30	2.85	1.36	0.319	0.051	0.025
	30-45	2.99	1.42	0.316	0.052	0.009
	45-60	3.19	1.53	0.374	0.058	0.010
	60-75	3.39	1.60	0.392	0.061	0.027
	75-90	3.52	1.67	0.343	0.055	0.032
30-40%	0-15	2.43	1.02	0.637	0.108	0.059
	15-30	2.50	1.05	0.588	0.103	0.044
	30-45	2.66	1.11	0.519	0.090	0.018
	45-60	2.87	1.22	0.491	0.084	0.022
	60-75	3.11	1.31	0.331	0.069	0.054
	75-90	3.27	1.40	0.274	0.057	0.075
40-50%	0-15	2.14	0.70	0.428	0.115	0.158
	15-30	2.21	0.72	0.612	0.139	0.155
	30-45	2.37	0.77	0.316	0.102	0.026
	45-60	2.59	0.86	0.530	0.133	0.039
	60-75	2.84	0.94	0.678	0.162	0.125
	75-90	3.03	1.02	0.609	0.143	0.145
50-60%	0-15	1.92	0.45	1.866	0.486	0.498
	15-30	1.99	0.47	1.150	0.310	0.273
	30-45	2.14	0.51	0.702	0.282	0.091
	45-60	2.36	0.58	0.305	0.192	0.077
	60-75	2.61	0.64	0.172	0.073	0.369
	75-90	2.81	0.71	-0.005	-0.002	-0.812

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